EXHIBIT 3

UNITED STATES DISTRICT COURT
EASTERN DISTRICT OF MICHIGAN
SOUTHERN DIVISION

IN RE FLINT WATER LITIGATION	Case No. 5:16-cv-10444-JEL-EAS Hon. Judith E. Levy

DECLARATION OF DR. SIDDHARTHA ROY

I, Siddhartha Roy, Ph.D., state and declare as follows:

I. INTRODUCTION AND QUALIFICATIONS

1. I am an environmental engineer. I earned my doctoral degree in Civil Engineering with an emphasis in Environmental Engineering from Virginia Polytechnic Institute and State University (Virginia Tech) College of Engineering in 2018. My PhD advisor at Virginia Tech was University Distinguished Professor and MacArthur "Genius" Fellowship awardee Dr. Marc Edwards. I received my Bachelor's of Technology degree in Chemical Engineering from Nirma University's Institute of Technology in 2010 and Masters in Environmental Engineering from Virginia Tech's College of Engineering in 2015. I am an Engineer-in-Training (E.I.T.; License #0420072931) for Environmental Engineering as designated by the State of

Virginia's Board for Architects, Professional Engineers, Land Surveyors, Certified Interior Designers and Landscape Architects since 2020. At Virginia Tech, I was a Water INTERface Interdisciplinary Graduate Education Fellowship (IGEP) recipient and earned a Graduate Certificate in Interdisciplinary Water and Health Science in 2014.

2. After graduating with a PhD in February 2018, I was a Postdoctoral Research Associate during April 2018-September 2020 and Research Scientist during October 2020-October 2022 with mentor Dr. Marc Edwards at Virginia Tech. I co-founded the US Water Study research team at Virginia Tech (www.uswaterstudy.org).

3. I am currently a Research Associate at the University of North Carolina (UNC) Water Institute, Gillings Schools of Global Public Health, UNC Chapel Hill.

4. For my research on lead in drinking water and associated health impacts in Flint, Chicago and other US communities, I was awarded the STAT Wunderkind Award by STAT News/The Boston Globe, Young Global Leadership Award by the International Water Association, Water Is Life Award by the American Civil Liberties Union Michigan, and Graduate Student of the Year Award by Virginia Tech. I was named one of the Top New Faces of Civil Engineering Professionals by the American Society of

Civil Engineers in 2019 and one of the top three finalists of the Early Career Award for Public Engagement with Science by the American Association for the Advancement of Science in 2020.

5. A complete description of my educational background and research work experience is appended as **Exhibit 1** to this declaration.

6. Notably for my work on this case, I am the co-author of two peer-reviewed articles reporting the results of biosolids analysis of lead release into drinking water in Flint, Michigan before, during, and after the city's use of the Flint River as its drinking water source:

    a. "Lead release to potable water during the Flint, Michigan water crisis as revealed by routine biosolids monitoring data," co-authored with Dr. Min Tang and Prof. Marc Edwards and published in 2019 in the journal *Water Research*. A copy of the article ("Roy et al. 2019"), including published supplemental information, is attached as **Exhibit 2**.

    b. "Efficacy of corrosion control and pipe replacement in reducing citywide lead exposure during the Flint, MI water system recovery," co-authored with Prof. Marc Edwards and published in 2020 in the journal *Environmental Science: Water Research & Technology*. A copy of article ("Roy and Edwards 2020"), including published supplemental information and a published addendum, is attached hereto as **Exhibit 3.**

II. SCOPE OF WORK

7. I have been retained by the law firms of Campbell Conroy & O'Neil P.C. and Mayer Brown LLP on behalf of Veolia North America to offer opinions in relation to the Flint Water Cases consolidated before the Honorable Judith E. Levy of the Eastern District of Michigan.

8. Specifically, the scope of my work is to offer opinions relating to my research on biosolids analysis of lead in drinking water in Flint, Michigan in the period 2010-2019.

9. My compensation for work on this litigation is $275, except for deposition and trial testimony, which is billed at $350 per hour.

10. I have not testified previously in court or at deposition.

11. My opinions offered here are based on my knowledge, education, training, and experience as a scientist and engineer. All opinions are offered to a reasonable degree of engineering and scientific certainty.

III. OPINIONS

A. <u>The Scientific Peer Review Process</u>

12. Many scientific studies are published in journals after they pass through the "peer review" process. Peer review is "an evaluation process in which journal editors and other expert scholars critically assess the quality and

scientific merit of the article and its research."[1] Typically, after authors submit their manuscript to a high-quality journal, a handling editor evaluates the submission and sends it out to experts (typically, 2-3 scholars) for critical review or, more commonly, rejects it outright. Expert reviewers carefully read the article, including the study hypotheses, methods, data collection, statistical analyses, graphs and tables, interpretation of the evidence, limitations of the study, and any conflicts of interest. The reviewers write up detailed review reports and submit them to the editor with recommendations for the manuscript (e.g., "Accept as is", "Major Revisions required", "Minor Revisions required," and "Reject"). I have also served as peer reviewer for 16 journals and have recommended "Major Revisions required" and "Reject" for several manuscripts authored by other researchers.

13. In a peer review, the journal editor takes all reviewer comments and their own assessment of the submitted article into consideration before making a decision. Manuscripts typically go through several rounds of revisions (usually, two rounds in my experience) and can get rejected even in later rounds, if authors cannot provide satisfactory responses to the reviewers, defend the quality of their scientific work, or make recommended changes to

[1] National Institutes of Health, National Library of Medicine (undated), *Peer-reviewed literature*, https://www.nlm.nih.gov/nichsr/stats_tutorial/section3/mod6_peer.html

the manuscript. The entire peer review process can sometimes take over a year. While the peer review process is imperfect, it is still an extremely difficult hurdle to clear at medium to high quality journals, which have a high rejection rate.

14. Two imperfect indicators of a peer reviewed article's success are the "impact factor" of the journal it was published in and the number of times it has been referenced or "cited" by scholars in later peer reviewed articles.

15. I have published 14 peer-reviewed journal publications, which have been collectively cited over 900 times.[2] These articles have appeared in high-impact journals, including *Water Research*, *International Journal of Hygiene and Environmental Health*, *Journal of Exposure Science and Environmental Epidemiology*, *Environmental Science: Water Research and Technology*, and *Environmental Science and Technology*, among others and are listed in Exhibit 1.

16. The key scientific findings discussed in this declaration are based on two peer-reviewed articles, Roy et al. 2019 and Roy and Edwards 2020, I published, alongside my co-authors Drs. Marc Edwards and Min Tang, in the journals *Water Research* (publisher: Elsevier) in May 2019 and in

[2] Google Scholar. https://scholar.google.com/citations?user=AW-b9OwAAAAJ

Environmental Science: Water Research and Technology (publisher: UK Royal Society of Chemistry) in August 2020. Each article was handled by the respective journal's editorial team and reviewed by at least two peer-reviewers. I have previously presented findings from these articles at the following scientific conferences: American Water Works Association Annual Conference and Exposition 2019 in Denver CO, American Water Works Association Water Quality and Technology Conference 2019 in Dallas TX, American College of Toxicology Annual Meeting 2019 in Phoenix AZ, American Water Works Association Virtual Summit on Water Quality and Infrastructure 2020 online, and American Chemical Society Fall 2021 Annual Conference online.

17. In supplement to our academic publications, my co-author Dr. Edwards and I also published a guest essay, attached as **Exhibit 4**, in *Undark* magazine (publisher: the KSJ Fellowship Program at MIT) in September 2020 sharing major findings from this research with the general public.

B. Limitations of official water lead levels available during the Flint Water Crisis (FWC) period

18. The City of Flint switched its water supply from Lake Huron water with orthophosphate via Detroit Water and Sewerage Authority (now, Great

Lakes Water Authority) to the local Flint River water without orthophosphate on April 25, 2014.

19. The official water lead data collected under the Lead and Copper Rule (LCR) as implemented by the City of Flint and overseen by Michigan Department of Environmental Quality during April 2014-August 2015, the first 16 months of the crisis, were unreliable and biased low for the following reasons: a) the LCR water sampling protocol included a flushing step prior to the 6+ hour stagnation period prior to sample collection, b) usage of small-mouthed bottles for sample collection that discouraged opening of faucets at full flow to allow for scouring of any loose lead particulates and thereby minimize the likelihood of their capture when filling up the bottles, c) less than 50% of water samples were collected from Tier-1 homes (i.e., those with confirmed lead service lines), and d) two high water lead samples were later dropped from the official 2015 LCR pool.

C. Wastewater-based epidemiology to track water lead levels

20. Wastewater-based epidemiology is a scientific field dedicated to monitoring chemicals or pathogens in wastewater to answer important water infrastructure or public health questions. Wastewater surveillance is being

increasingly conducted for pharmaceuticals and personal care products,[3] illicit drugs,[4] antibiotic-resistance genes,[5] and pathogens like SARS-CoV-2 during the COVID-19 pandemic.[6]

21. Sewage sludge (or, biosolids) have been monitored at US wastewater plants for over 25 years under the U.S. Environmental Protection Agency's Part 503 Rule, including for heavy metals like lead, copper, zinc, cadmium, and nickel that are released due to corrosion of domestic plumbing and service lines.

22. The following are the general advantages of biosolids monitoring as compared to monitoring via tap water samples, and specifically LCR monitoring: a) samples are measured at the wastewater treatment facility and completely independent of LCR monitoring, b) sampling protocol and analytical methods have remained consistent for decades and this data is available for many wastewater facilities since the 1990s, and c) in the absence of large industrial sources, metals, including lead, released from

[3] Wang, J., Wang, S., 2016. Removal of pharmaceuticals and personal care products (PPCPs) from wastewater: a review. J. Environ. Manag. 182, 620e640.
[4] van Nuijs, A.L., Castiglioni, S., Tarcomnicu, I., Postigo, C., de Alda, M.L., Neels, H., Zuccato, E., Barcelo, D. and Covaci, A., 2011. Illicit drug consumption estimations derived from wastewater analysis: a critical review. Science of the Total Environment, 409(19), pp.3564-3577.
[5] Su, J.Q., An, X.L., Li, B., Chen, Q.L., Gillings, M.R., Chen, H., Zhang, T. and Zhu, Y.G., 2017. Metagenomics of urban sewage identifies an extensively shared antibiotic resistome in China. Microbiome, 5(1), pp.1-15.
[6] Wurtzer, S., Waldman, P., Ferrier-Rembert, A., Frenois-Veyrat, G., Mouchel, J.M., Boni, M., Maday, Y., Marechal, V. and Moulin, L., 2021. Several forms of SARS-CoV-2 RNA can be detected in wastewaters: implication for wastewater-based epidemiology and risk assessment. Water Research, 198, p.117183.

domestic plumbing are major contributors to metals in biosolids, and d) majority of lead in wastewater (~87%±8%) is removed during treatment and concentrated in biosolids.

23. This method can also overcome severe logistical and statistical limitations encountered in official LCR sampling: a) composite (24x7) and routine (e.g., monthly) tracking of city-wide or population-level lead vs. "first draw" water samples collected from 50-100 homes every 6 months-3 years under LCR, b) monitoring at the wastewater plant vs. inside private homes, c) track system-level changes resulting from corrosion control treatment changes or pipe replacements.

24. There are some possible limitations to the biosolids method, none of which were prominent in the case of Flint: a) the wastewater plant serves a geographical area substantially different from that served by the drinking water plant of interest, b) biosolids sample analyses and data collection methods were modified during a time period of interest, c) missing or infrequent data collection by the wastewater plant, d) combined sewer systems that transport both urban runoff (e.g., from rainfall or hydrant flushing) and domestic wastewater, and e) significant presence of lead and heavy metals in effluents discharged by industry.

D. <u>Method and key findings from the Flint biosolids research</u>

25. We requested monthly biosolids lead and other metals data from Michigan Department of Environmental Quality/City of Flint's Water Pollution Control Facility and childhood blood lead data from Hurley Medical Center (Dr. Mona Hanna-Attisha), both for the period 2011-19. We further utilized water lead data from five city-wide sampling rounds conducted using a three-bottle protocol by our Virginia Tech team and Flint residents in August 2015 (n=268 Flint homes), March 2016 (n=186 Flint homes), July 2016 (n=176 Flint homes), November 2016 (n=164 Flint homes), and August 2017 (n=150 Flint homes).

26. None of the previously outlined limitations for biosolids analyses were encountered in Flint during our study period (roughly, 2011-19) to any meaningful degree: a) the service areas for Flint's water and wastewater plants substantially overlapped, b) the biosolids analyses and data collection methods remained unchanged, c) biosolids samples were analyzed each month and typically in the first six days, d) Flint's stormwater was not discharged into sewers, and e) over 95% of wastewater in Flint was domestic in origin and the industrial sources still in operation had largely eliminated lead sources.

27. In our analyses, biosolids lead mass were strongly correlated with water lead levels (i.e., equally weighted 90th percentile values of first, second and third draw water lead concentrations) from the city-wide sampling rounds for the corresponding months. This correlation allowed us to estimate monthly water lead levels for the entire study period (2011-19).

28. More than three quarters of the extra lead release to water captured in biosolids during the water crisis versus an identical 18-month period before the crisis, occurred during June-August of 2014.

29. This trend was also observed for the percentage of young children (i.e., below 6 years of age) with blood lead at or above the then-CDC "level of concern" 5 µg/dL metric, which was nearly twice as high during those three months of Summer 2014 vis-à-vis the remaining months of the crisis.

30. Our analyses revealed a previously unknown spike in water lead levels in April-May 2011 that coincided with a spike in childhood elevated blood lead levels, which was attributed to "random variation" in a prior independent study on blood lead trends in Flint children by Flint pediatrician Dr. Hernan Gomez and colleagues.[7] Lead in biosolids and in children's blood were

[7] Gomez, H.F., Borgialli, D.A., Sharman, M., Shah, K.K., Scolpino, A.J., Oleske, J.M., Bogden, J.D., 2018. Blood lead levels of children in Flint, Michigan: 2006-2016. J. Pediatr. 197, 158e164

higher in mid-2011 when Flint was served by Lake Huron water than reported during the entire Flint Water Crisis.

31. The biosolids data further indicated that lead levels have dropped to historical lows in 2018-19 after Flint's switchback to Lake Huron water with orthophosphate (October 2015), more than tripling of the orthophosphate corrosion control dosage (December 2015), implementation of an extensive flushing program, replacement of brass faucets, and replacement of over 80% of the City's lead and galvanized iron service lines.

32. Similar decreases in trends were observed for 2018-19 in childhood blood lead and 90th percentile water lead levels in official LCR and independent sampling in Flint.

33. Biosolids lead data also successfully tracked the impact of lead pipe replacements and the effectiveness of more than tripling of orthophosphate dose for corrosion control. Specifically, the lead and copper, lead and zinc, and copper and zinc mass pairs in biosolids were strongly correlated before (2011-14), during (2014-15) and two years (2015-17) after the crisis indicating corrosion from lead pipes, lead-bearing and other plumbing. However, for 2018-19, only the copper and zinc correlation remained significant indicating a) the impact of replacing of over 80% of lead and galvanized iron pipes, and the effectiveness of enhanced orthophosphate

corrosion control dosing and b) installation of copper pipes and brass (i.e., containing copper and zinc) containing valves, faucets, and fixtures.

34. When Flint achieves 100% lead service line elimination, our biosolids analyses indicate that a) domestic plumbing containing leaded brass and solder would become the dominant source of lead to water and biosolids, b) a net reduction of 72-84% in overall lead release would be achieved vis-à-vis levels in 2013 before the Flint River water switch underscoring the success of lead pipe replacements and enhanced corrosion control implementation in Flint.

I declare that the foregoing statements are made to a reasonable degree of professional certainty, and that the foregoing statements are true and correct to the best of my knowledge and information.

Siddhartha

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Siddhartha Roy, Ph.D.
Carrboro, North Carolina

Dated: 02/02/2023

EXHIBIT 1

Siddhartha Roy, Ph.D., EIT
Environmental Engineer
Carrboro NC (United States)
Email: sidroy@vt.edu
Web: www.siddhartharoy.org

Nationalities: India (Citizen by birth); USA (Permanent Resident: EB1-A "Extraordinary Ability").

ACADEMIC HISTORY AND CERTIFICATIONS

Virginia Tech, College of Engineering – Blacksburg, VA
2018 *Ph.D. in Civil Engineering (program: Environmental Engineering)*
+ Graduate Student of the Year
2015 *M.S. in Environmental Engineering*
+ "Water INTERface" IGEP Fellow
2014 *Interdisciplinary Water and Health Sciences Graduate Certificate*
Nirma University, Institute of Technology – Ahmedabad, India
2010 *B.Tech. in Chemical Engineering*
+ First Class with Distinction
State of Virginia, Engineer in Training (EIT)
2020 *Environmental Engineering License #0420072931*

PROFESSIONAL APPOINTMENTS

2022+ **The Water Institute, University of North Carolina**, Chapel Hill, NC
Research Associate (Oct 2022-present)

2012-22 **Virginia Tech Department of Civil and Environmental Engineering**, Blacksburg, VA
Research Scientist (Oct 2020-Oct 2022)
Postdoctoral Research Associate, US Water Study Team founding co-leader (2018-20)
Graduate Research and Teaching Assistant, Laboratory of Dr. Marc Edwards (2012-18)

2010-12 **Cognizant Technology Solutions**, Merck Europe Support Project, Pune, India
Programmer Analyst (Business Intelligence and Data Analytics), Innovation Lead

HONORS AND AWARDS

2016-22

- STAT Wunderkind 2021, STAT News/The Boston Globe
- IWA Young Leadership Award 2020-22, International Water Association (IWA)
- ASCE New Face of Civil Engineering Professionals, American Society of Civil Engineers (ASCE)
- AAAS Early Career Award for Public Engagement with Science / Finalist, American Association for the Advancement of Science (AAAS)
- WEF Water Leadership Institute Class of 2018, Water Environment Federation (WEF)
- Paper on perverse incentives in academia placed in Top 1% of Engineering (cited 300+ times)
- Scientist Sentinel: Civic Engagement & Leadership Program (competitive; declined), COMPASS
- Who's Who in America list
- Rising Stars of the Water Industry, WQP Magazine

- Graduate Student of the Year, Virginia Tech
- Virginia AWWA Graduate Student Scholarship, VA American Water Works Association
- Ut Prosim Scholar, Virginia Tech
- Graduate Student Service Excellence Award, Virginia Tech
- National Video Competition Second Prize, Association of Environmental Engineering and Science Professors (AEESP) for the documentary: https://youtu.be/t0ZNYHB7TvE

20013-15

- Water Is Life Award, American Civil Liberties Union (ACLU) - Michigan
  For "your courage to shine a light on the Flint water crisis protecting the health of countless residents"
- Third Prize (National), Fresh Ideas Poster Competition w/ K Phetxumphou at AWWA ACE 2015
- Citizen Scholar Award, Virginia Tech
- Class of 2014: Outstanding Winter Graduate, Virginia Tech
- Engineers Without Borders-USA Global Leadership Program Scholarship, Black and Veatch Fdn
- Interdisciplinary Graduate Education Program (IGEP) Fellowship 2014-15, Virginia Tech
- Student Business Concept Challenge Finalist, Virginia Tech Knowledge Works

Flint Water Study Team Awards (2015-18)

- Kellogg Foundation Community Engagement Scholarship Award, W. K. Kellogg Foundation
- UPCEA Engagement Award, University Professional and Continuing Education Association
- The Jean and Leslie Douglas Pearl Award, Cornell Douglas Foundation
- Special Recognition, Earth Day Network Climate Leadership Gala, Washington DC
- Alumni Award for Outreach Excellence, Virginia Tech *(wrote the award proposal)*
- Newsmaker of the Year, Virginia Professional Communicators
- Public Integrity Award, American Society for Public Administration
- Citizen Scholar Award, Virginia Tech *(wrote the award proposal)*
- Proclamation (Commendation), City of West Hollywood California
- Certificate of Appreciation, City of Flint Michigan, 2015

TED TALK

Science in service to the public good (over 1.4 million views; debuted on TED.com in 04/2017).

SCHOLARLY PUBLICATIONS

Peer-reviewed publications
(#: peer-reviewed conference paper, ^: advised undergraduate student, *: corresponding author)
Per Google Scholar: total citations = 976; h-index = 10

1. Roy, S.* and M.A. Edwards. Addressing the Preprint Dilemma. *International Journal of Hygiene and Environmental Health.* doi: 10.1016/j.ijheh.2021.113896.
2. Roy, S.* and M.A. Edwards. Are there excess fetal deaths attributable to waterborne lead exposure during the Flint Water Crisis? Evidence from Bio-kinetic Model Predictions and Vital Records. *Journal of Exposure Science and Environmental Epidemiology.* doi: 10.1038/s41370-021-00363-z
3. Roy, S.*, K. Mosteller, M. Mosteller, K. Webber, V. Webber, S. Webber, L. Reid, L. Walters, and M.A. Edwards. 2021. Citizen science chlorine surveillance during the Flint, Michigan federal water emergency. *Water Research.* doi: 10.1016/j.watres.2021.117304.

4. # Lightner, T.*, S. Roy, M.A. Edwards and J. London. 2021. Centering the public: A narrative analysis of engineering graduate students' journeys navigating public-inspired science work. *ASEE Annual Conference and Exposition 2021*, Jul 25-28, 2021.
5. Roy, S.* and M.A. Edwards. 2020. Efficacy of Corrosion Control and Pipe Replacement in Reducing Citywide Lead Exposure during the Flint, Michigan Water System Recovery. *Environmental Science: Water Research & Technology*. doi: 10.1039/d0ew00583e
6. Roy, S.*, M. Tang, and M.A. Edwards. 2019. Lead Release to Potable Water during the Flint, Michigan Water Crisis as revealed by Routine Biosolids Monitoring Data. *Water Research*. doi: 10.1016/j.watres.2019.05.091
7. Roy, S.* and M.A. Edwards. Citizen Science During the Flint, Michigan Federal Water Emergency: Ethical Dilemmas and Lessons Learned. *Citizen Science: Theory and Practice*. doi:10.5334/cstp.154
8. Roy, S.* and M.A. Edwards. Preventing another Lead (Pb) in Drinking Water Crisis: Lessons from Washington DC and Flint MI contamination events. *Current Opinion in Environmental Science & Health*. doi:10.1016/j.coesh.2018.10.002
9. Roy, S.*, P. Smith^, G. House^, and M.A. Edwards. 2018. Cavitation and Erosion Corrosion Resistance of Nonleaded Alloys in Chlorinated Potable Water. *CORROSION*. doi:10.5006/2939
10. Roy, S.* and M.A. Edwards. 2018. Interactive Effects of Water Chemistry, Hydrodynamics, and Precipitated Calcium Carbonate Causing Erosion Corrosion of Copper in Hot Water Recirculation Systems: Case Study and Experimental Work. *CORROSION*. doi:10.5006/2937
11. Pieper, K.J., M. Tang, R. Martin, L. Walters, J. Parks, S. Roy, C. Devine, and M.A. Edwards*. 2018. Evaluating Water Lead Levels during the Flint Water Crisis. *Environmental Science & Technology*. doi:10.1021/acs.est.8b00791
12. Roy, S.*, J.M. Coyne, J.A. Novak, and M.A. Edwards. 2017. Flow-induced failure mechanisms of copper pipe in potable water systems. *Corrosion Reviews*. doi:10.1515/corrrev-2017-0120
13. Edwards, M.A.* and S. Roy. 2016. Academic Research in the 21st Century: Maintaining Scientific Integrity in a Climate of Perverse Incentives and Hyper-competition. *Environmental Engineering Science*. doi:10.1089/ees.2016.0223.
    > Top 1% cited paper in Engineering academe; 'Most Read' paper in journal's history; 250,000+ downloads; Trended #1 on Reddit Science; Featured in Science News & Chemistry World
14. # Roy, S.* and M.A. Edwards. 2016. Effects of Calcium Carbonate precipitation on erosion corrosion of non-leaded brass fittings in potable hot water systems. *Proc. NACE CORROSION 2016*, Mar 6-10, 2016, Vancouver, Canada.
15. Phetxumphou, K., S. Roy, B.M. Davy, P.A. Estabrooks, W. You, and A.M. Dietrich*. 2016. Assessing clarity of message communication for mandated USEPA drinking water quality reports. *Journal of Water and Health*, doi:10.2166/wh.2015.134
16. Roy, S.*, K. Phetxumphou, A.M. Dietrich, P.A. Estabrooks, W. You, and B.M. Davy. 2015. An Evaluation of the Readability of Drinking Water Quality Reports: A National Assessment. *Journal of Water and Health*, doi:10.2166/wh.2015.194
17. # Lambrinidou, Y.*, W.J. Rhoads, S. Roy, E. Heaney, G. Ratajczak, and J. Ratajczak. 2014. Ethnography in Engineering Ethics Education: A Pedagogy for Transformative Listening. *ASEE Annual Conference and Exposition*, Jun 15-18 2014, Indianapolis, IN.

Peer-reviewed conference presentations *(* implies invited; ** implies conference poster; "peer-reviewed" = abstract reviewed before acceptance)*

1. ** Roy, S., K. Mosteller, M. Mosteller, K. Webber, V. Webber, S. Webber, L. Reid, L. Walters, and M.A. Edwards. Citizen science chlorine surveillance during the Flint, Michigan federal water emergency. IWA Disinfection + DBPs, Jun 27-Jul 1, 2022, Milan, Italy.

2. Roy, S. and M.A. Edwards. NSF Fellows' attitudes on the research climate in STEM academia. AEESP Conference 2022, Jun 28-30, 2022, St. Louis, MO.
3. ** Roy, S. and M.A. Edwards. Exposing Infrastructure Inequality and Environmental Injustice through a Citizen Science-supported Graduate Training Program: The US Water Study Experience. C*Sci 2022, May 23-26, 2022, Virtual.
4. Roy, S., K. Mosteller, M. Mosteller, K. Webber, V. Webber, S. Webber, L. Reid, L. Walters, and M.A. Edwards. Citizen science chlorine surveillance during the Flint, Michigan federal water emergency. AWWA WQTC 2021, Nov 7-10, 2021, Tacoma WA.
5. Wait, K., S. Roy, and M.A. Edwards. Can Iron and Manganese Deposits on Copper and Stainless-Steel Plumbing Produce Rapid Pipe Failures at Water Temperatures >60°C? AWWA WQTC 2021, Nov 7-10, 2021, Tacoma WA.
6. ** Edwards, M.A. and S. Roy. A "Public Inspired Science" Graduate Training Program. US National Academy of Engineering Promising Practices, 2021.
7. Roy, S. and M.A. Edwards. Are there excess fetal deaths attributable to waterborne lead exposure during the Flint Water Crisis? Evidence from Bio-kinetic Model Predictions and Vital Records. American Chemical Society (ACS) Fall 2021, Aug 22-26, 2021, Atlanta GA.
8. ** Odimayomi, T., S. Roy, and M.A. Edwards. Tracking Lead (Pb) Release to Potable Water through Biosolids Data in Six Cities across North America: Challenges and Opportunities. AWWA ACE 2021, Jun 14-17, 2021.
9. Roy, S., M. Tang, and M.A. Edwards. Documenting Continued Reductions in Lead Release to Potable Water in the Aftermath of the Flint, MI Water Crisis. AWWA Virtual Summit on Water Quality and Infrastructure, Dec 8-10, 2020.
10. Edwards, M.A., J. Purchase, K.G. Lopez, and S. Roy. Engineering Ethics and Citizen Science in Underserved Communities: Experiences of The US Water Study Team. AEESP Converging COVID-19, environment, health, and equity conference, Oct 16-Nov 20, 2020.
11. Roy, S., Pieper, K.J., Battle, C., Lopez, K.G., and M.A. Edwards. Citizen science monitoring for India's water sector: Tools and protocols from the US experience. AWWA India Annual Conference, Dec 13-14, 2019, Mumbai, India.
12. Roy, S., M. Tang, and M.A. Edwards. Lead (Pb) in water, childhood lead exposure, and adverse pregnancy outcomes during the Flint Water Crisis: Quantifying the "unknown". American College of Toxicology Annual Meeting, Nov 17-19, 2019, Phoenix, AZ.
13. Roy, S., M. Tang, and M.A. Edwards. Lead (Pb) Exposure and Associated Adverse Health Outcomes During the Flint, Mich. Water Crisis: Quantifying the "Unknown." AWWA WQTC, Nov 3-7, 2019, Dallas, TX.
14. Roy, S. and M.A. Edwards. The Promises and Perils of Citizen Science and Community Engagement witnessed in the Flint Water Crisis. International Society of Environmental Epidemiology, Aug 25-28, 2019, Utrecht, the Netherlands.
15. Roy, S. and M.A. Edwards. Anatomy of Public Health Crises: Flint MI and Washington D.C. Lead in Water Emergencies. International Society of Environmental Epidemiology, Aug 25-28, 2019, Utrecht, the Netherlands.
16. Roy, S., M. Tang, and M.A. Edwards. Lead Release to Potable Water during the Flint, Michigan Water Crisis as revealed by Routine Biosolids Monitoring Data. AWWA ACE, Jun 9-12, 2019, Denver, CO.
17. * Roy, S. Citizen science to monitor water quality in underserved communities and emergencies: Tools and protocols from the US experience. U.S.-Jordan Conference on Development and Policy Responses to the Syrian Refugee Crisis, Jun 4-7, 2019, Blacksburg, VA.

18. Roy, S. and M.A. Edwards. Citizen Science During the Flint, Michigan Federal Water Emergency: Ethical Dilemmas and Lessons Learned. AEESP Conference, May 14-16, 2019, Tempe, AZ.
19. Roy, S. and M.A. Edwards. A Case Study of Postmodern Science Anarchy and Ethics: The Flint, MI Federal Emergency. Forum on Philosophy, Engineering and Technology 2018, May 30-Jun 1, 2018, College Park, MD.
20. Roy, S. and M.A. Edwards. WRF 4658: Cavitation and Erosion Corrosion Resistance of Nonleaded Alloys in Chlorinated Potable Water. AWWA WQTC, Nov 12-16, 2017, Portland, OR.
21. Roy, S. and M.A. Edwards. Cavitation and Erosion Corrosion Resistance of Nonleaded Alloys in Chlorinated Potable Water. AWWA ACE, Jun 11-14, 2017, Philadelphia, PA.
22. * Roy, S. and M.A. Edwards. Science for the Public Good vs. Perverse Incentives in Academia. AAAS Annual Meeting, Feb 16-20, 2017, Boston, MA.
23. * Roy, S. and M.A. Edwards. The Flint Water Crisis: Responding to a Public Health Emergency. E.U. SAFEWATER Conference, Nov 23-24, 2016, Zurich, Switzerland.
24. Roy, S. and M.A. Edwards. Revisiting the public health tragedy in Flint and why we are ill-equipped to prevent another. APHA Annual Meeting and Expo, Oct 29-Nov 2, 2016, Denver CO.
25. Pieper, K.J., A. Katner, S. Roy, and M.A. Edwards. Lead in Water Equation: Understanding variables that influence lead in drinking water. UNC W&H, Oct 10-14, 2016, Chapel Hill, NC.
26. Roy, S. and M.A. Edwards. The Flint MI Water Crisis: Lessons in Communicating Science and Influencing Public Discourse with Research. AWWA ACE, Jun 19-22, 2016, Chicago, IL.
27. * Roy, S., K. Phetxumphou, A.M. Dietrich, P.A. Estabrooks, W. You, and B.M. Davy. Communicating Water Quality: Available tools for evaluation. UNC Water and Health Conference, Oct 26-30, 2015, Chapel Hill, NC.
28. Roy, S. and M.A. Edwards. Role of water hardness precipitation and flashing cavitation in erosion corrosion of copper in potable water systems. AWWA ACE Jun 7-10 2015, Anaheim CA.
29. ** Phetxumphou, K.,^ S. Roy^, B.M. Davy, P.A. Estabrooks, W. You, and A.M. Dietrich. Evaluating readability and clarity of USEPA mandated Drinking Water Quality Reports: A National Assessment. AWWA ACE, Jun 7-10, 2015, Anaheim, CA. ^equal contribution
30. Roy, S. Revitalizing Ethics Training of STEM Graduates: The Tonawanda NY Experience. DuPont Summit on Science, Technology & Environmental Policy, Dec 5 2014, Washington, DC.
31. Roy, S. and M.A. Edwards. Erosion Corrosion of Copper as a function of temperature, flow rates and water hardness. AWWA ACE, Jun 8-12, 2014, Boston, MA.

Technical Reports

1. Purchase, J.M., S. Roy, A. Katner, K.J. Pieper and M.A. Edwards. 2022. Practical Applications of NSF/ANSI 53 Lead Certified Filters: Investigating Lead Removal, Clogging and Consumer Experience. *Final Report prepared for U.S. Housing and Urban Development*.
2. Roy, S., P. Smith, G. House, and M.A. Edwards. 2018. Corrosion of Nonleaded Pump Impeller Alloys in Chlorinated Potable Water. *Water Research Foundation* (WRF) Project 4658 Final Report. WRF. Denver, CO.
3. Roy, S., G. House, and M.A. Edwards. 2018. Comparative Resistance of Six Copper Alloys to Erosion Corrosion in Simulated Potable Water. *Final Report prepared for Chase Brass.*
4. Roy, S. and M.A. Edwards. 2016. Hard $CaCO_3$ Particles Formed by Water Heating Exacerbate Copper Erosion Corrosion. *Final Report prepared for Copper Development Association*.

Editorials and columns in popular press (not peer-reviewed)

1. Edwards, M., A. Pruden, S. Roy, K. Faust, S. Masten. *After we tried to correct claims about 'deadly' water filters in Flint, we were accused of scientific misconduct—and that was just the beginning.* Retraction Watch. May 2022
2. Edwards, M., C. Yang, and S. Roy. *Who dares to speak up? An interview with Tuskegee whistleblower Peter Buxtun.* American Scientist. Jul-Aug 2021
3. Roy, S. *What can we learn from misinformation on scientific matters in the water space?* International Water Association. November 2020
4. Roy, S. and M. Edwards. *From Sewage Sludge, a New Perspective on the Flint Water Crisis*. Undark. September 2020 (syndicated: Mother Jones)
5. Roy, S. and M. Edwards. *Flint water crisis shows the danger of a scientific dark age.* CNN. March 2019
6. Roy, S. and M. Edwards. *Intègres comme des coureurs du Tour de France*. Books. March-April 2018
7. Roy, S. and M. Edwards. *Science is a public good in peril – here's how to fix it.* Aeon. Nov. 2017
8. Phetxumphou, K., S. Roy B.M. Davy, P.A. Estabrooks, W. You, and A.M. Dietrich. *Write Consumer Confidence Reports Customers Can Understand.* OpFlow. February 2017
9. Roy, S. *The Hand-in-Hand Spread of Mistrust and Misinformation in Flint.* American Scientist. January-February 2017
10. Rhoads, W.J., R. Martin and S. Roy. *We helped uncover a public health crisis in Flint, but learned there are costs to doing good science.* The Conversation (syndicated: PBS, Scientific American, Huffington Post). January 2016

PUBLIC SCHOLARSHIP AND SELECTED PRESS

Science Documentaries, Podcasts and Websites

1. Executive Producer. *The Public-inspired Science Podcast*. Two seasons on Apple iTunes.
2. Executive Producer and Videographer. *The U.S. Water Study documentary series.* YouTube.
3. Producer and Narrator. *Flint Water Study – An ode to environmental engineers.* Award-winning science documentary: https://youtu.be/t0ZNYHB7TvE
4. Creator and curator. *USWaterStudy.org*
5. Creator and curator. *FlintWaterStudy.org* (over 1 million views) and social media (Facebook and Twitter).
   My Twitter (@flintwaterstudy) engagement was the subject of a peer-reviewed journal article by science communication researchers (doi: 10.1177/1075547017751948).
6. Producer and Videographer. *Public Inspired Science.* US Water Study: https://youtu.be/hnbXQ4Z0evo
7. Script and Video-segment producer. *MacArthur Foundation 100&Change grant proposal video abstract "Science as a public good"*: https://youtu.be/j8Y2Q7WPLOE
8. Producer and Videographer. Water sampling videos for Flint, Michigan (https://youtu.be/dEQDaPws2xk), California schools (https://youtu.be/pxg9X9NMy4g) and Virginia schools (https://youtu.be/dcmgP4VEx50).

Invited Keynote Lectures, Talks, and Expert Panels

1. AIChE (Webinar), 2016.
2. AIHA/ASSE Conference (Denver, CO), 2017.
3. Boston University (Boston, MA), 2022.
4. Cal Poly (San Luis Obispo, CA), 2022.
5. Chandler-Gilbert CC (Chandler, AZ), 2018.
6. Chapman University (Orange, CA), 2021
7. George Walton Academy (Monroe, GA), 2020.
8. Georgetown University (Washington DC), 2022.
9. ComSciCon 2016 (Cambridge, MA), 2016.
10. Kids' Tech University (Blacksburg, VA), 2018.
11. IWA Emerging Water Leaders Forum, 2021.
12. Interpublic Group (virtual), 2022.
13. Linda Hall Library of Science Engineering, and Technology (Kansas City, MO), 2020.
14. Louisiana State Univ. (Baton Rouge, LA), 2020.
15. MIT (Cambridge, MA), 2018.
16. Middlebury College (Middlebury, VT), 2018.
17. NJ Institute of Technology (Newark, NJ), 2021.
18. Northwestern University (Evanston, IL), 2016.
19. Ohio AWWA (Columbus, OH), 2015.
20. Phillips Exeter Academy (Exeter, NH), 2016.
21. Princeton University (Princeton, NJ), 2018.
22. Purdue University (West Lafayette, IN), 2021.
23. Queen's University (Canada; Virtual), 2022.
24. Rising Silo Brewery (Blacksburg, VA), 2018.
25. Rutgers University (New Brunswick, NJ), 2022.
26. Science Museum of VA (Richmond), 2017, 2019.
27. Science Writers Conf. (San Antonio, TX), 2016.
28. Slovenian Academy of Sciences and Arts (Ljubljana, Slovenia), 2019.
29. Stanford University (Stanford, CA), 2021.
30. St. Lawrence Univ. (Canton, NY), 2022.
31. TCA Hollywood Press (Pasadena, CA), 2017.
32. Tufts University (Medford, MA), 2018.
33. University of Arizona (Tucson, AZ), 2022.
34. University at Buffalo (Buffalo, NY), 2020.
35. UCLA (Virtual), 2022.
36. University of Florida (Gainesville, FL), 2022.
37. University of Houston (Houston, TX), 2021.
38. Univ. of Maryland (College Park, MD), 2017.
39. UMass Amherst (Amherst, MA), 2020.
40. Univ. of Notre Dame (South Bend, IN), 2017.
41. University of Virginia (Virtual), 2022.
42. Univ. of Wisconsin Madison (Virtual), 2022.
43. Virginia AWWA/VWEA WaterJAM 2016 Keynote (Virginia Beach, VA), 2016.
44. VA Historical Society (Richmond, VA), 2017.
45. Wesleyan University (Middletown, CT), 2018.
46. W. Mich. University (Kalamazoo, MI), 2016.
47. WGBH Idea Lab (Cambridge, MA), 2016.
48. World Health Organization (Geneva, Switzerland), 2017.

Media Coverage (Science Documentaries and Movies)

1. PBS NOVA. 'Poisoned Water', 2017 *(on Netflix; winner of AAAS Kavli Science Journalism award).*
2. BBC. FLINT, 2020.
3. Virginia Tech. 'Cicero', 2019
4. Discovery (UK)/National Geographic (US). Disasters Engineered. Season 02. Ep. 08. Contaminated Waters. 2020-21.

Media Coverage (Newspapers and Magazines)

Selected listing in alphabetical order.

1. ABC News: Flint Water Crisis: How a Water Study Researcher Would Address the Damage (Jan 19, 2016)
2. American Scientist: Moving Forward After Flint (May-June 2016 issue)
3. Associated Press: Flint lead problem could be eased by recoating old pipes (Jan 22, 2016)
4. ASCE News: Young Engineer Finds His Calling Through Flint Water Crisis Solutions (Feb 2019)
5. ATTN: Flint, Michigan Has Been Charging Its Residents for Toxic Water (Jan 19, 2016)
6. ATTN: The Water in Flint Is Better, but People Aren't Using It (Oct 21, 2016)
7. Bloomberg BNA: Flint, Mich., Didn't Follow Drinking Water Controls (Oct 20, 2015)
8. Burlington Free Press: Vermont schools have lead in their water supply. How concerned should you be? (Jan 27, 2020)

9. CEP Magazine (AIChE's flagship journal; profile feature): Pursuing Science for the Public Good (December 2016 issue)
10. Chicago Tribune (front page): Flint researchers find alarming levels of lead in Cicero, Berwyn tap water, suggesting thousands of older homes at risk (Aug 10, 2018)
11. Christian Science Monitor: How to fix Flint's lead pipe problem (Jan 23, 2016)
12. Chronicle of Higher Education: The Accidental Ethicist (Oct 2, 2016)
13. Engineer's Forum: PUZZLING PIPES: Civil engineers plumb corrosion mystery (September 2015 issue)
14. Five Thirty-Eight: What Went Wrong In Flint (Jan 26, 2016)
15. Grist: Shift Happens, one PB&J at a time (Dec 3, 2016)
16. Healthline: How toxic is the water in Flint (Jan 25, 2016)
17. Jacobin: Capitalism Is Ruining Science (July 2018 issue)
18. Michigan Radio: Team testing Flint water for lead sample by sample (Sep 6, 2015)
19. Michigan Radio: New study questions some of the citizen science projects during Flint's water crisis (Mar 8, 2019)
20. My Suburban Life: Testing by local organization, Virginia Tech finds high lead levels in Berwyn, Cicero water (Aug 14, 2018)
21. Notre Dame Science: Virginia Tech researchers explain the Flint water crisis (Dec 8, 2016)
22. National Science Foundation: Flint water crisis: For young engineers, a lesson on the importance of listening (Mar 23, 2016)
23. Pittsburgh Tribune-Review.
24. SciDev: India, MENA region face severe water crisis (Aug 15, 2019)
25. Scientific American: Water Wand (Jun 2020)
26. STAT News: Lessons from a Flint water crisis researcher about building trust in science during the pandemic (Nov 18, 2021)
27. St. Louis Post-Dispatch: Districts move to test water for lead after elevated levels found in some St. Louis schools (Aug 25, 2016)
28. The American Prospect: Beyond Flint: How Local Governments Ignore Federal Water Standards (Feb 24, 2016)
29. The Dallas Morning News: Disabled Texans in three state homes have been drinking water with Flint-level amounts of lead (May 13, 2016)
30. Flint Journal: Meet the key figures in NOVA's 'Poisoned Water' feature on Flint (May 2017)
31. Flint Journal: Researchers say sewage data holds clues to Flint water crisis (May 30, 2019)
32. The Guardian: A hidden scandal: America's school students exposed to water tainted by toxic lead (Mar 6, 2019)
33. The New York Times (centerspread): As Flint Fought to Be Heard, Virginia Tech Team Sounded Alarm (Feb 6, 2016)
34. The Roanoke Times: Virginia Tech researchers fought for Flint in water crisis (Jan 23, 2016)
35. Virginia Tech Magazine: Fighting for Flint: A Virginia Tech team exposes lead poisoning (Spring 2016 issue)
36. Virginia Tech Magazine: Tapping the Ripple Effect (Fall 2018 issue)
37. WIRED: Ripple Effect: The crisis in Flint isn't over. It's everywhere. (Jun 2016 issue)
38. WIRED: The Flint Water Crisis Is Bigger Than Elon Musk (Jul 12, 2018)

Media Coverage: Television

1. FOX17: Virginia Tech scientist talks 'Flint water crisis' with WMU students, staff (Feb 10, 2016)
2. Sky News UK: Dirty Water Supplies 'Poisoning Public Trust' (May 30, 2016)
3. WDBJ7: Sunday morning TV panel (Jan 2016)
4. TRT World: Has Flint's water crisis been solved? (Apr 19, 2018)
5. WSLS10: Virginia Tech researchers announce Flint water is safe (Sep 17, 2017)

Media Coverage: Podcasts and Radio

1. Mother Jones' Inquiring Minds (2017)
2. Science Soapbox (2016)
3. The Nature of Cities (2016)
4. The Story Collider (2017)
5. International Water Association (2021)
6. International Water Association (2020)
7. Vanguard STEM. (2016)
8. BBC World Service (2016)
9. Iowa Public Radio (NPR): Iowa's Drinking Water: Could Flint Happen Here? (June 2016)
10. KCRW's To The Point: Lead in America's Water Systems (March 2016)
11. Minnesota Public Radio (NPR): This American Moment: Restoring the public's faith in science and expertise (November 2018)
12. WMUK (NPR): WSW: Flint's Lesson About Science And Ethics (February 2016)
13. WUFT (NPR): What Led The Alachua County School District To Install Water Filters To Prevent Lead Contamination (October 2018)

RESEARCH CONTRACTS AND GRANTS ($5,000 and over)

1. Spring Point Partners, LLC ($3,000,000). *Exposing Infrastructure Inequality in America: Leveraging Success and Building Capacity* (2017-present). Co-Investigator.
2. ACX ($25,000). *Citizen science sampling for waterborne opportunistic pathogens including Legionella* (2022-on). Lead Investigator and Primary Author.
3. Water Research Foundation ($60,000). 4658: *Corrosion of Nonleaded Pump Impeller Alloys in Chlorinated Potable Water* (2016-18). Lead Investigator and Primary Author.
4. Chase Brass ($16,200). Technical Assistance Program: Erosion Corrosion in Nonleaded Alloys (2016-17). Lead Investigator and Primary Author.
5. Union of Concerned Scientists and EPA College/Underserved Community Partnership Program. ($10,000). Lead in Water Pilot Project for public schools near Georgia College, Tuskegee University and UNC Wilmington (2016-17). Primary Coordinator.
6. Flint Water Study Crowdfunding ($100,000+). GoFundMe to recover discretionary funds directed to Flint (2016). Co-written/co-led with Dr. Marc Edwards.
7. [Development/Service] Engineers Without Borders ($26,450). Guatemala Boarding School Sanitation Project. Primary Author. Funds from Boeing, Pratt & Whitney and Bechtel (2013-15).

PROFESSIONAL SERVICE

Referee for peer-reviewed journals and conference proceedings

American Journal of Public Health
Citizen Science: Theory and Practice
CORROSION
Corrosion Reviews
Environmental Engineering Science
Environmental Justice
Environmental Science and Technology
Environmental Science and Technology Letters
ES&T Water
ES: Water Research & Technology
IWA World Water Congress 2022, Denmark
International J. of Hygiene and Env. Health
Forensic Sciences Research
Journal of Water and Health
Proceedings of the National Academy of Sciences
Water Research
WIRES: Water
Utilities Policy

Federal Advisory Boards

US Environmental Protection Agency, Board of Scientific Counsellors - *Social and Community Science* federal advisory committee, 2022-onward

Journal Editorial Boards

Invited to join: *Frontiers in Environmental Health* in 2022 (declined) and *International Journal of Environmental Research and Public Health* in 2020 (declined)

Research Proposal/Award/Federal Recommendations Reviewer

CDC National Institute for Occupational Safety and Health – Lead Pipe Replacement Advisory, 2022
University of Wisconsin Water Resources Institute – Research Proposals, 2022
National Science Foundation ENG/CBET Program – Research Proposals, 2021
NC Water Resource Research Institute – Research Proposals, 2020
AAAS Kavli Science Journalism Awards – Science Reporting: In Depth, 2020
AAAS IF/THEN Ambassadors (100 women in STEM as role models for middle school girls), 2019
Graduate Women in Science National Fellowship Program, 2019
VT Graduate Research Development Program – student research proposals, 2013

Expert Judge

Virginia State Science and Engineering Fair, 2020
Paul E. Torgersen Graduate Research Excellence Competition, Virginia Tech, 2019
U.S. Stockholm Junior Water Prize, Blueridge Highlands Science Fair, Radford VA, 2018
Young Professionals Poster Competition, AWWA Annual Conference, Denver CO, 2017

Conferences and Workshops

- Conference Moderator (2x), UNC Water and Health Conference, Oct 24-28 2022, Chapel Hill NC Organizer and Moderator, "The Science and Politics of Journal Retractions" webinar, HxEES, May 25, 2022, Virtual
- Organizer and Moderator, "Fighting the coronavirus pandemic: Evidence-based approaches from Environmental Engineers" webinar, HxEES, Jul 29, 2020, Virtual
- Conference Session Chair, "Special Case Studies" at AWWA India Annual Conference and Exposition, Dec 13-14, 2019, Mumbai, India
- Conference Workshop Chair, "Water Quality and Citizen Science 101" teaching workshop at UNC Water and Health Conference 2019, Oct 11 2019, Chapel Hill NC
- Conference Moderator, "Disinfection Byproduct Health Impacts and Compliance Strategies" at AWWA WQTC 2019 in Dallas TX (Nov 3-7, 2019)
- Co-organizer, US-Jordan "Transformational Ideas to Improve Development and Policy Response to Forced Displacement" conference on the Syrian refugee crisis, Jun 4-7 2019, Blacksburg VA

ORGANIZATIONAL MEMBERSHIPS

Current: Association of Environmental Engineering and Science Professors (AEESP), Heterodox Academy (HxA), International Water Association (IWA), Society of Toxicology (SOT). Previously active: American Society of Civil Engineers (ASCE), American Water Works Association (AWWA), Engineers Without Borders USA (EWB-USA), National Association of Corrosion Engineers (NACE), Society of International Development–US (SID-US), Water Environment Federation (WEF).

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EXHIBIT 2

Water Research 160 (2019) 475–483

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Lead release to potable water during the Flint, Michigan water crisis as revealed by routine biosolids monitoring data

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ABSTRACT

Routine biosolids monitoring data provides an independent and comprehensive means to estimate water lead release pre-, during and post-Flint Water Crisis (FWC). The mass of potable plumbing-related metals (i.e., lead, cadmium, copper, nickel and zinc) in sewage biosolids strongly correlated with one another during the FWC ($p < 0.05$). A simple parametric regression model based on 90th percentile potable water lead measurements (WLL90) from five city-wide citizen science sampling efforts August 2015–August 2017 was strongly correlated to corresponding monthly lead mass in biosolids [Biosolids-Pb (kg) = 0.483 x WLL90 (μg/L) + 1.79; $R^2 = 0.86$, $p < 0.05$]. Although total biosolids lead increased just 14% during the 18 months of the FWC versus the comparable time pre-FWC, 76% of that increase occurred in July–September 2014, and the corresponding percentage of Flint children under 6 years with elevated blood lead ≥ 5 μg/dL (i.e., %EBL5) doubling from 3.45% to 6.61% in those same three months versus 2013 ($p < 0.05$). %EBL5 was not statistically higher during the remaining months of the FWC compared to pre-FWC or post-FWC. As expected, lead in biosolids during the FWC, when orthophosphate was not added, was moderately correlated with water temperature ($R^2 = 0.30$, $p < 0.05$), but not at other times pre- and post-FWC when orthophosphate was present. Tripling the orthophosphate dose post-FWC versus pre-FWC and some lead pipe removal, decreased lead in biosolids (and %EBL5) to historic lows (2016–2017 vs. 2012–2013; $p < 0.05$), supporting the effectiveness of these public health interventions in reducing childhood water lead exposure.

1. Introduction

After a citizen science collaboration between Flint residents and our Virginia Tech research team exposed citywide water lead contamination in August 2015, there has been widespread concern regarding consumer exposure to lead during the Flint Water Crisis (FWC) (Bellinger, 2016; Edwards, 2015; Pieper et al., 2017, 2019; Roy and Edwards, 2019a, 2019b). The FWC started April 25, 2014, when Lake Huron water from Detroit with a 1 mg/L orthophosphate dose for corrosion control was replaced with higher corrosivity Flint River water without orthophosphate. This change increased lead release from lead service lines (LSLs), galvanized iron pipe (GIP), leaded solder and brass (Del Toral, 2015; Edwards et al., 2018; Masten et al., 2016; Pieper et al., 2017, 2018).

Although the trajectory of water lead levels (WLLs) in the home of one Flint resident is relatively well understood (Pieper et al., 2017), almost nothing is known about the magnitude and timing of lead release throughout the rest of the city between April 2014 and August 2015 – the official water lead data that was collected is considered nearly useless due to the fact compliance samples did not meet criteria under the National Primary Drinking Water Regulations and the federal Lead and Copper Rule (LCR). For example, the requirement that at least 50% of compliance samples must be collected from homes with LSLs was not met (Pieper et al., 2018). The official sampling results were also biased low, by pre-flushing homes the evening before the six-hour stagnation time and use of small-mouthed bottles (Edwards, 2015; Grevatt, 2016; Milman and Glenza, 2016; Del Toral, 2015). In contrast, starting with Virginia Tech's standardized citywide sampling campaign in hundreds of Flint homes August 2015 onwards, there is relatively good understanding of WLL trends because these sampling events were repeated at the same homes using the same sampling protocol in March 2016, July 2016, November 2016 and August 2017 (Pieper et al., 2018).

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The lack of data on water lead levels and associated uncertainties with human exposure from April 2014–August 2015 have led to angst, speculation, proxy research and controversy (Bouffard, 2018; Carmody, 2019; Clark and Filardo, 2018; Gómez and Dietrich, 2018; Haynes, 2019; Taylor et al., 2016; Roy, 2017). The use of routine childhood blood lead level (BLL) monitoring data to indirectly assess the severity of the water lead exposure (e.g., Hanna-Attisha et al., 2016; Kennedy, 2016; Zahran et al., 2017; Gómez et al., 2018; Gómez et al., 2019), relies on a dataset of children mostly 1.5–6 years age, who are actually the group least likely to reveal water lead impacts because this group is at greatest risk of exposure to lead paint and dust (Levin et al., 2008; Edwards et al., 2009; Triantafyllidou and Edwards, 2012; Hanna-Attisha et al., 2016). The pregnant women and formula-fed infants who are at greatest risk of lead exposure from drinking water (i.e., >85% of lead exposure for many infants fed reconstituted formula is typically from water) do not have routine blood lead measurements for analysis because it is assumed that federal corrosion control laws would limit water lead exposures (Edwards et al., 2009; Edwards, 2013; Triantafyllidou and Edwards, 2012; USEPA, 1988; USEPA, 1991).

Despite the acknowledged weaknesses in the elevated blood lead (EBL) data used in prior ecological assessments of the FWC and some heated debate about their interpretation, there is good agreement about the overall trends (Gómez et al., 2018; Hanna-Attisha, 2018a,b; Kennedy, 2016; Zahran et al., 2017). Specifically, the proportion of Flint children with elevated blood lead levels ≥5 μg/dL (%EBL5) roughly doubled during the FWC (April 2014–October 2015), especially in the neighborhoods where Virginia Tech's water sampling revealed greatest lead in water risk (Gómez et al., 2018; Hanna-Attisha et al., 2016). However, there is nonetheless ongoing dismay about "not knowing" trends in water lead exposure that occurred during the 18 months of the FWC (Banner, 2018; Gómez et al., 2018; Gómez et al., 2019; Graham, 2016; Kruger et al., 2017; Oleske et al., 2016).

To address these concerns, we explored the novel hypothesis that routine monthly analysis of metal mass in biosolids (i.e., digested sewage sludge) at the Flint wastewater treatment plant represents a composite sample tracking the mass of metal release from plumbing to the Flint water distribution system. Metals (including lead) in municipal wastewater are often dominated by release from potable water plumbing (Alam and Sadiq, 1989; Boulay and Edwards, 2000; Comber and Gunn, 1996; Isaac and Boothroyd, 1996; Hargreaves et al., 2018; Karvelas et al., 2003; Murphy and Pierides, 2004; NYCDEP, n.d.; Santos-Echeandía, 2009; Sörme and Lagerkvist, 2002; Toffey, 2016; Goodman, 1984; Isaac et al., 1997) and a majority of Pb ($87 \pm 8\%$) in wastewater is typically removed during treatment and concentrated in the biosolids (Goldstone et al., 1990; Goldstone and Lester, 1991). This general idea was recently exploited in attempts to estimate water lead levels in drinking water of ancient Rome (Delile et al., 2014, 2017). Biosolids in wastewater began to be monitored in the U.S. starting in early 1980s and, therefore, this dataset is available for many municipal systems starting before the Lead and Copper Rule monitoring began in 1991 (USEPA, 1991; WEF, 2011). In Flint less than 5% of the wastewater is derived from industry, which has largely eliminated its lead sources (Case, 2018), further increasing the likelihood that the lead captured in Flint biosolids is mostly derived from domestic plumbing release to potable water.

If the hypothesis is valid that lead release from potable water plumbing is a substantial source of lead in Flint biosolids, it would also be expected that:

a) metal mass released from plumbing and captured in biosolids would be higher during the FWC (especially in warmer months) when orthophosphate corrosion inhibitor was absent, but lower and independent of temperature during time periods when orthophosphate was present (Boulay and Edwards, 2000; Del Toral et al., 2013; Deshommes et al., 2013; Masters et al., 2016b; Lytle and Schock, 1996).
b) Lead in biosolids will correlate with other common metals characteristic of premise plumbing materials (cadmium, copper, zinc and nickel) that sloughed from pipe scale when corrosion control was interrupted (Alam and Sadiq, 1989; AWWA, 2011; Comber and Gunn, 1996; Gonzalez et al., 2013; Lytle and Schock, 1996; Pieper et al., 2017).
c) lead mass in biosolids would correlate with available datasets collected for citywide lead in water, and possibly the incidence of %EBL5 in Flint children during the anomalous time when lead in water was a dominant source of childhood lead exposure (Table S1).

2. Experimental methods

Water temperature data, %EBL5 cases for children under six years of age within the City of Flint, MI, and pre-existing data on metal concentrations in biosolids were used in this retrospective ecological study analyzed for three periods (Table S2): May 2011–April 2014 ("pre-FWC"), May 2014–October 2015 ("during FWC") and November 2015–November 2017 ("post-FWC"). The term "post-FWC" for lead, reflects the fact that bottled water and filters were provided to all residents for health protection after November 2015, reducing the likelihood of consumer exposure even as water lead remained elevated. This also coincided with a switchback to Lake Huron water and boosted orthophosphate dosing that began to reduce water and biosolids lead.

2.1. Water temperature

Daily temperature data at the effluent of the Flint water treatment plant was obtained from archived monthly Michigan Department of Environmental Quality water quality reports 2011–2017 (https://www.michigan.gov/flintwater/).

2.2. Trends in elevated blood lead (EBL)

Deidentified summaries of BLL measurements for Flint children were provided by Hurley Medical Center's Dr. Mona Hanna-Attisha for May 2011–November 2017, and used to calculate percentage of children under six with elevated blood lead levels (%EBL5) using conventions described elsewhere (Hanna-Attisha et al., 2016; Hanna-Attisha, 2018a,b). To account as best we can, for a slight lag between increased WLLs and elevations of lead in children's blood considering the blood lead half-life of 28–36 days (ATSDR, 2007; Triantafyllidou and Edwards, 2012), correlations used %EBL5 data paired with biosolids lead from the same month (i.e., %EBL5 cases detected May 2016 are paired with biosolids data from May 2016).

2.3. Metals in biosolids

Monthly metal concentrations in biosolids (lead, cadmium, copper, nickel and zinc; mg/kg on a dried weight basis) and total monthly biosolids production (kg) were provided by MDEQ. A composite sample of biosolids was collected from an effluent digester pipe at the City of Flint wastewater plant (Case, 2018) early each month from May 2011 to November 2017. Seventy seven percent of the biosolids samples were collected between the 1st and 6th of each month. The metal concentrations were measured per Standard Method SW 6020A (APHA, AWWA and WEF, 1998).

The monthly mass of metal in biosolids was estimated by multiplying the metal biosolids concentration by the total biosolids production.

A one month offset was used between WLL90 data from Virginia Tech's citywide sampling campaigns with metals in biosolids data, to partly account for the two weeks (plant target = 13–15 days) of biosolids retention time (WEF, 2011; Case, 2018) in the plant digester and another few days of activated sludge detention time. For example, water samples collected from homes throughout the month of August 2015 were paired with total lead mass in biosolids early September 2015.

2.4. Metals in water, including water lead levels (WLLs)

Five city-wide tap water sampling events using a three-bottle first, second and third draw protocol were executed in a citizen science collaboration between Flint residents and our Virginia Tech team in August 2015 (n = 268), March 2016 (n = 186), July 2016 (n = 176), November 2016 (n = 164) and August 2017 (n = 150) and the results were published elsewhere (Pieper et al., 2018). All water samples were acidified by adding 2% HNO_3, digested for 16 + hours to adequately dissolve and capture particulate lead and analyzed on an Inductively Coupled Plasma Mass Spectrometry (ICP-MS) for 28 elements including lead, cadmium, copper, nickel and zinc (all μg/L) per Standard Method 3125 B (APHA, AWWA and WEF, 1998). For data quality assurance and quality control, blanks and spikes of known concentrations were measured on the ICP-MS after every 10–15 samples.

Sequential samples of lead, copper and zinc in water of 23 Flint homes that participated in all five USEPA sequential sampling rounds (January–March, May, July, September, and November 2016) during the 2016 federal emergency response were obtained from the USEPA's website (USEPA, 2017; Lytle et al. 2019).

Mean composite metal sample values using the weighting [1/3 x (mean first draw) + 1/3 x (mean second draw) + 1/3 (mean third draw)] were calculated in the five Virginia Tech and the five USEPA sampling rounds to test co-occurrence of zinc, lead and copper. Similar calculations could not be made for nickel and cadmium in the Virginia Tech data because the mean release was below the detection limit.

A representative weighted average 90th percentile WLL (WLL90) was calculated, using a weighted average of 1/3 x (90th percentile first draw lead), 1/3 x (90th percentile second draw lead) and 1/3 x (90th percentile third draw lead), to reflect importance of lead release from all three types of water in human exposure (Sandvig et al., 2008) for each Virginia Tech sampling round. The 90th percentile has been the standardized reporting measure of WLL in the United States since the federal Lead and Copper Rule was adopted in 1991.

For a comparison between the WLLs in Washington D.C 1997–2006 and the FWC, a modified composite 90th percentile WLL (MWLL90) was calculated based on reported first draw lead levels from our previous studies, because no third draw data and only one set of extensive second draw WLLs exists for Washington D.C (Edwards et al., 2009; Edwards, 2013). Specifically, to characterize human exposure risk to water lead, we used a 50:50 weighting of measured 90th percentile first draw and measured 90th percentile second draw for the FWC, using a viable LCR sampling pool comprised of 50% homes with LSLs (17 homes with LSLs and 17 homes with lead solder/galvanized iron) back-calculated as described in Pieper et al. (2018). For Washington D.C., we estimated the corresponding weighted 90th percentile water lead level (50:50 first and second draw weighting), using our previously published 90th percentile first draw lead calculations, and an assumption that the 90th percentile second draw lead was equal to 1.375 × 90th percentile first draw lead, per calculations of 6,162 first and second draw samples collected during summer 2003.

2.5. Statistical analyses

All statistical analyses were conducted in RStudio (version 3.3.2) and/or Microsoft® Excel® (version 2016). A p value of <0.05 with an alpha value (α) of 0.05 was selected to determine statistical significance. The Pearson's coefficient correlation test was used to examine the associations between monthly biosolids lead mass, % EBL5 and other variables. Parametric linear regressions were performed between: a) composite WLL90 from all five Virginia Tech sampling rounds (μg/L) and lead in biosolids (kg) in the corresponding month, b) MWLL90 from all five Virginia Tech sampling rounds (μg/L) and lead in biosolids (kg) in the corresponding month, and c) %EBL5 for 18 months of the FWC and lead in biosolids (kg) in the corresponding month. The runs test for randomness was conducted for lead in biosolids (kg) for 18 months of the FWC (NIST/SEMATECH, 2012).

3. Results and discussion

3.1. Temporal trends of plumbing-related metals in biosolids

Levels of premise plumbing related metals (cadmium, copper, lead, nickel and zinc) in Flint's monthly biosolids were correlated before, during and post-FWC (Figs. 1 and S1). All five metals spiked markedly in the summer of 2014 when there was no corrosion control during the FWC, and it is hypothetically possible this was due to general sloughing of pre-existing scale from all plumbing surfaces (Masten et al., 2016; Olson et al., 2017; Pieper et al., 2017, 2018). The mass of all five plumbing-related metals in biosolids were strongly correlated ($p < 0.05$) with each other in all three time periods (Table S3). At the home of Flint "Resident Zero", there was a similar correlation between all five of these plumbing related metals during intensive water sampling in April 2015 (Pieper et al., 2017), when this home pipe scale was clearly sloughing at high levels—hence, the system wide correlation is a logical extension of what occurred in this one home.

Considering the five Virginia Tech citywide potable water sampling rounds, strong correlations were observed between the mean composite measures of lead and copper ($R^2 = 0.89$, $p < 0.05$), and copper and zinc ($R^2 = 0.83$, $p < 0.05$) (Table S4). Similar trends were observed for all five rounds of USEPA data, with lead and copper ($R^2 = 0.93$, $p < 0.05$), and copper and zinc ($R^2 = 0.78$, $p < 0.05$). Interestingly, there was no significant co-occurrence observed for these metals for a given draw in both datasets (i.e., first, second or third draw), but only for the weighted composite result. This is expected given that the first draw water is often derived from a pure copper pipe, whereas the second draw sample is often from a service line with pure lead or galvanized iron pipe (i.e., first draw has highest copper and relatively low lead, second draw has highest lead and almost no copper).

The monthly lead in biosolids was not correlated with monthly average water temperature pre- and post-FWC ($p > 0.05$) as expected for systems dosed with orthophosphate for corrosion control (Masters et al., 2016b), but they were moderately correlated during the FWC when orthophosphate was not dosed ($R^2 = 0.30$, $p < 0.05$) (Table S1). The water temperature of the shallow Flint River water source versus Lake Huron, fluctuated much more in both summer and winter months during FWC compared to pre- or post-FWC (Fig. 1), producing a greater possible effect of temperature on metal release from plumbing (Deshommes et al., 2013; Masters et al., 2016b).

The tripling of orthophosphate dose to Lake Huron water (3 mg/L

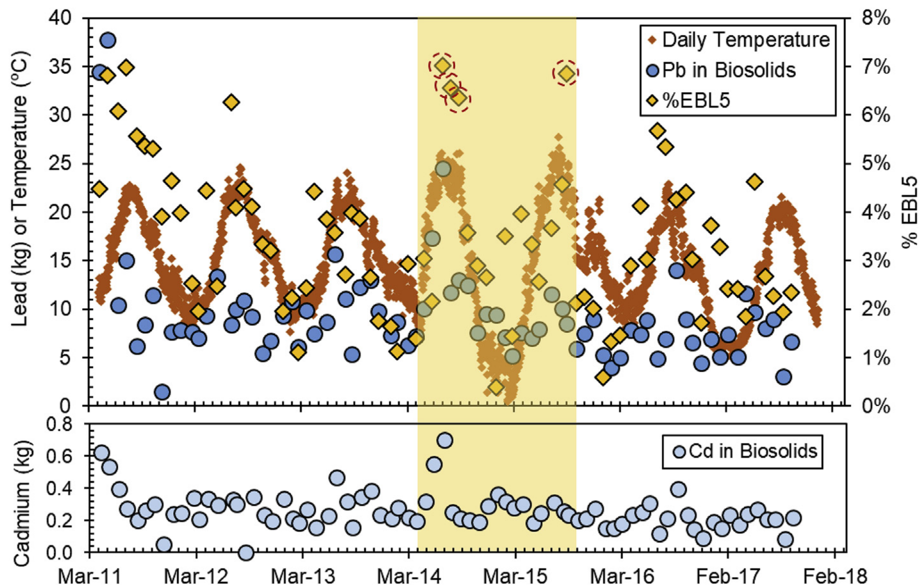

Fig. 1. Monthly cumulative lead (Pb) mass in biosolids, percent of children with elevated blood lead levels (% EBL5) (i.e., ≥5 μg/dL) and water temperature (upper) during May 2011–November 2017. The four months with peak %EBL5 during the FWC (circled in red) occurred in July–September 2014 and August 2015. Representative data for a plumbing related metal (Cd), also illustrates prominent spike immediately after the water switch to Flint River in April 2014 (lower). The light orange area represents the time span of the FWC. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

total PO_4) starting December 9, 2015 per USEPA recommendations decreased overall lead release from the distribution system to historic lows post-FWC (2016–17; average lead in biosolids = 6.9 kg/month) versus pre-FWC (2012–13; average = 9.3 kg/month), suggesting that the higher phosphate dosages caused lower lead release from the plumbing even after the interrupted corrosion control during the FWC (two-tailed paired *t*-test; $p < 0.05$). This trend of declining potable lead levels was confirmed by third party independent sampling which revealed a 90th percentile first draw WLL of 4 μg/L in late January 2019 (Masten and Doudrick, 2019).

3.2. Biosolids lead correlates strongly with citywide water lead measurements

The WLL90 calculated from each round of citywide citizen science sampling and the monthly lead in biosolids of the corresponding month were strongly correlated ($R^2 = 0.86$, $p < 0.05$, N = 5; Fig. 2), supporting the hypothesis that biosolids lead reflects citywide release of lead to water from plumbing. The modeled relationship [Biosolids-Pb (kg) = 0.483 x WLL90 (μg/L) + 1.79], has an intercept of 1.79 kg, which might represent a portion of lead loading to the sewage plant per month independent of that

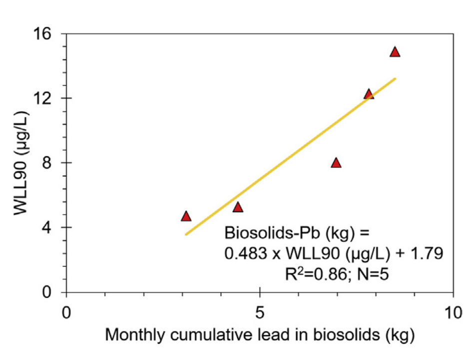

Fig. 2. Monthly cumulative lead mass (kg) in biosolids was correlated with WLL90 from five rounds of water sampling campaigns ($R^2 = 0.86$, $p < 0.05$, N = 5).

released from plumbing, such as lead in wastewater from all non-plumbing sources and 5% wastewater flow from industry (Case, 2018).

Recent research made a rough estimate that ~18 g lead leached on average from each Flint LSL (Olson et al., 2017). Considering a recent rough estimate of 12,000 homes with LSLs in the City of Flint (City of Flint, 2019), a total extra lead release of 216 kg from LSLs to water would be predicted during the FWC. If the typical 87% of this lead release to water was captured in biosolids (Goldstone et al., 1990; Goldstone and Lester, 1991), the resulting prediction of 188 kg lead is of similar magnitude to the 184 kg cumulative lead measured in biosolids during the FWC in this research.

In terms of possible confounding factors, the stormwater in Flint is not discharged to sewers, reducing the likelihood that surface water runoff or hydrant flushing of water would influence the results (Busch, 2014; Emery, 2014; Fonger, 2014; Roy and Edwards, 2015; Case, 2018). Moreover, hydrant flushing uses water from mains that has not contacted the building plumbing that contains the Zn, Cu, Pb, Cd and Ni metals, so any variation in flushing water from hydrants does not affect the release of these metals to drinking water or their mass in biosolids. Following the switch, the total mass of biosolids (dry weight basis) produced in May to July 2014 (average = 317 metric tons) was more than twice as high as the biosolids produced the prior year (May 2013–Apr, 2014; average = 140 metric tons), before eventually stabilizing to pre-crisis levels after switching back to Lake Huron source water (Fig. S2). As long as the unidentified source of these higher biosolids did not contain a significant mass of lead, the correlation between lead mass in biosolids and the lead release to potable water would still be valid, as appears to be the case for data presented herein.

3.3. Lead in biosolids and elevated blood lead

Lead in water exposure is not typically considered to be a dominant correlate to lead in blood (Triantafyllidou and Edwards, 2012), especially for the age group whose blood lead is routinely monitored, when corrosion control is effective or the population is protected against elevated lead in water. This expectation was

verified by a lack of correlation between biosolids lead (reflecting water lead exposure) and %EBL5 post-crisis ($p > 0.05$; Table S1). During the 18 months pre- and during the FWC, there were only very weak correlations between %EBL5 and biosolids lead (during FWC, $R^2 = 0.22$; pre-FWC, $R^2 = 0.12$; $p < 0.05$).

Overall, it appears that monthly lead mass in biosolids does seem to track lead release from plumbing to potable water, but biosolids lead is only slightly predictive of overall childhood exposure for the age group of children whose blood lead is tested and considered least sensitive to water exposure. Several decades ago, it was predicted that the typical 2-year-old child obtained only 20% of their lead exposure from water on average, with the remainder from food, dust and other sources (USEPA, 1988). The fact that there are only slightly significant correlations between biosolids lead and %EBL5 for this age group both pre-FWC and during the FWC, suggests that lead in water is not normally a dominant source of exposure for this age group, even though other sources of lead exposure have been increasingly controlled since 1990 when the 20% blood lead from water estimate was made (Triantafyllidou and Edwards, 2012; USEPA, 1988).

The overall downward trends of lead in biosolids and childhood lead exposure are generally consistent with those observed nationally (Gómez et al., 2018; Hargreaves et al., 2018; Toffey, 2016; USEPA, 2009). Lead in biosolids was in a clear downtrend during the pre-FWC time period from 12 kg/month (May 2011–October 2012) to 9 kg/month (November 2012–April 2014). This downtrend is also reflected in decreasing mean %EBL5 from 4.71% to 2.76% in Flint over the same time period similar to trends nationwide (CDC, 2018; Gómez et al., 2018).

There are only two major exceptions to the overall %EBL5 and biosolids lead downtrend. The first was pre-FWC in 2011, where an unexplained peak in monthly biosolids lead correlated to a peak in %EBL5. Specifically, the average lead in biosolids for May–October 2011 of 18.7 kg/month corresponded to a very high mean %EBL5 of 5.91% over that time period. Gomez and colleagues (2018) attributed the 2011 spike in %EBL5 to a “random variation,” but the biosolids data indicate that lead in wastewater was also anomalously high in this April-May 2011 time period well before the FWC began in 2014. Looking more closely at the 2011 biosolids lead spike, we note that the lead levels were 115–185% above the Ni trendline and 30–70% above the Cd trendline, and during this time period lead was not correlated with other metals originating from premise plumbing corrosion (Fig. S3a). We speculate that this anomaly may have somehow been linked to treatment upsets or other events during record Detroit rainfall, which was national news in that exact time period (Bienkowski, 2013). ***Regardless, a key point is that both biosolids lead and %EBL5 spiked higher in 2011 than at any other point reported in this research, including during the FWC.***

The second exception occurred shortly after the source water was switched to Flint River in April 2014. The total biosolids lead mass during 18-month intervals before, during FWC and after the FWC were 161.5 kg, 184 kg, and 129 kg, respectively. Of the total 23 kg (or ~14% overall increased mass) extra biosolids lead mass during versus pre-FWC, 76% came in July–September of 2014 versus July–September 2013 (Fig. 3). A runs test for randomness analysis confirms that this biosolids lead mass spike in 2014 was not random ($p < 0.05$). The corresponding %EBL5 roughly doubled from 3.45% to 6.61% in those three months of 2014 versus 2013 ($p < 0.05$), and this was also the only time period in which %EBL5 was statistically higher during the FWC than pre- or post-FWC (Fig. 3). This 2014 biosolids lead spike was also directly on the trendline for other biosolids metals derived from plumbing materials (e.g., Ni and Cu - Fig. S3b), reinforcing the belief that this spike in biosolids lead (and associated spike in %EBL5) was due to scale

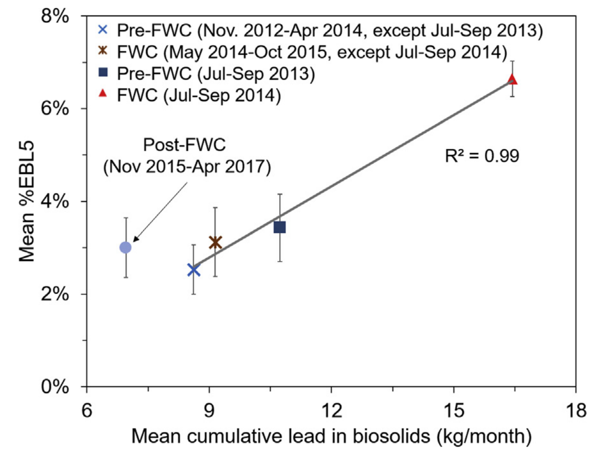

Fig. 3. Mean cumulative lead mass in biosolids (kg/month) correlated with mean % EBL5 for four time intervals pre- and during FWC ($R^2 = 0.99$, $p < 0.05$). Error bars indicate 95% confidence intervals for %EBL5. Due to water protective measures and a dramatic increase in EBL testing frequency by Federal Emergency Management Agency (FEMA), the post-FWC result is excluded from the regression.

sloughing from plumbing. In the 18 months post-FWC, the total lead in biosolids dropped 30% (~55 kg) and mean %EBL5 was 3.00% (Fig. 3).

After Virginia Tech's drinking water advisory in August 2015 and then Hurley Medical Center's September 2015 press conference showed increased blood lead in Flint children, the water source was switched back to Lake Huron water with corrosion control and decisive public health interventions were implemented to protect the public from high WLLs (Hanna-Attisha et al., 2016; State of Michigan, 2016; Pieper et al., 2018). The lead in biosolids decreased to 7.5 kg/month and mean %EBL5 decreased to 3.12% over the following year (November 2015–October 2016).

With recovery of corrosion control in the distribution system and implementation of enhanced corrosion inhibitor dosing (~3 mg/L as PO_4 starting December 9 2015), the lead in biosolids and mean %EBL5 was further decreased to historical lows of 6.7 kg/month and 2.58% (November 2016–October 2017), respectively. Clearly, the public health interventions of bottled water and lead filters reduced %EBL5 incidence back to historical lows, and %EBL5 and biosolids lead were decoupled, even as WLLs remained above federal standards through June 2016 as indicated by both the State of Michigan official data on residential/sentinel sampling and Virginia Tech's citizen science water lead monitoring (MDEQ, 2018; Pieper et al., 2018).

3.4. Contrast and comparison to other data

If it is assumed that the net biosolids lead minus the baseline 1.79 kg of non-plumbing lead (Figs. 2 and S4) reflects the true trend in water lead release and exposure, a perspective is provided on the FWC that is remarkably consistent with most existing published research on WLL or using the %EBL5 proxies. After the switchback in October 2015, the official lead in water data started meeting federal standards in late 2016, and the corresponding lead in biosolids also declined back to levels considered normal at the start of this decade (Fig. S5). Blood lead levels and water lead levels have also recently dropped to historic lows in Flint (Gómez et al., 2018; MDEQ, 2018; Pieper et al., 2018; Gómez et al., 2019; Masten and Doudrick, 2019; Lytle et al., 2019).

These results also help address some speculation regarding changes in childhood lead exposure in Flint. Specifically, the 2014 blood lead spike in Flint children did not likely originate from

children having more contact with contaminated soil in summer months as was recently speculated (Laidlaw et al., 2016), because the high lead in biosolids co-occurred with release of lead from premise plumbing. Thus, our data supports recent analyses by Centers of Disease Control and Prevention (CDC) and others, that also indicated soil was not a major contributor to this 2014 blood lead spike based on independent reasoning (Kennedy, 2016; Sadler et al., 2017). Moreover, speculation that a drop in blood lead observed in the months of Apr-Sep 2014 to Sep 2014–Sep 2015 is due to "boil water advisories" that caused consumers to switch to bottled water (Zahran et al., 2017), is not necessary because the drop in %EBL5 is shown herein to reflect a drop in WLLs in that time period.

Finally, this analysis provides evidence that the public health interventions of lead filters and bottled water were highly effective, severing any link between %EBL5 to lead in water and biosolids ($p > 0.05$, Table S1).

3.5. Historical perspectives on the Flint Water Crisis

This analysis fills major knowledge gaps regarding the trajectory of the FWC in relation to lead in water and human exposure. In particular, the monthly lead in biosolids reached a peak of 24.5 kg during the warmer months (May–October) of the crisis in 2014, but lead release steadily declined thereafter to less than half of that value (11.5 kg) for the same time period in 2015. Moreover, the average and maximum biosolids lead measurements during the FWC in 2015 were comparable to those pre-FWC in summer 2012 and summer 2013, suggesting that WLLs throughout the city might have declined from the start of the FWC in summer 2014 as lead was depleted and sloughed from scale (Olson et al., 2017). This analysis strongly suggests that the "worst" lead exposure during the FWC was restricted to June–August 2014 (captured in biosolids lead mass during July–September 2014), as is further confirmed by the significant elevation in %EBL5 associated with those months. The overall biosolids lead data directly contradicts prior speculation by ourselves and others, that water lead levels and associated exposures, progressively increased during the 18 months of the FWC.

Our analysis can also help put the potential exposures occurring during the FWC into context, versus routine USEPA 90th percentile first draw lead levels that are reported in other cities, and also in comparison to the other major water lead contamination event of this century in Washington D.C. 2001–2004 (Roy and Edwards, 2019a). Virginia Tech's citywide sampling event in August 2015, did detect a very significant lead contamination problem, with an estimated 90th percentile of 27 μg/L (first draw) for a back-calculated legitimate USEPA LCR monitoring event with 50% lead pipes (Pieper et al., 2018). If it is assumed that the 2.8X higher lead in biosolids in June 2014 vis-à-vis August 2015 is directly proportional to overall 90th percentile lead in water at that time [as supported by the strong correlation in other time periods; Biosolids-Pb = 0.37 x MWLL90 + 1.41 ($R^2 = 0.66$; $p < 0.05$; one-sided t-test for Pearson r)], it would suggest a 90th percentile lead first draw in the range of 76.8–98.5 μg/L in the worst (outlier) month of the FWC (June 2014) versus the EPA action level of 15 μg/L.

But first draw lead is only one part of the human exposure picture. The 2001–2004 DC Lead crisis was noteworthy because second draw was often much higher than first draw (Edwards and Dudi, 2004; Edwards et al., 2009; Edwards, 2013), whereas in Flint, the opposite was true (Pieper et al., 2018). If a simple composite exposure is considered based on 50% first draw and 50% second draw weighting (MWLL90), the 62.4 μg/L in the outlier month of June 2014 of the FWC would be in the range of the water lead observed in the 2001–2004 DC Lead Crisis (Fig. 4), but the DC exposures were much worse at all other times and the exposure was

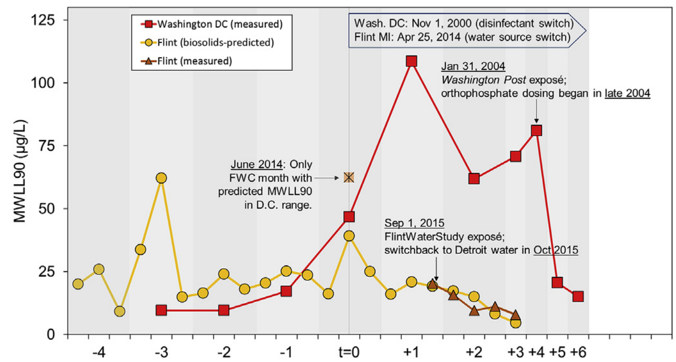

Fig. 4. Calculated MWLL90 levels from Washington D.C. lead in drinking water crisis, compared to estimated MWLL90 levels during the Flint, MI water crisis (FWC) as predicted from biosolids lead (this paper; Fig. 2) or that measured during five citizen science sampling rounds (method of Pieper et al., 2018). Washington D.C. data is yearly for 1997–2006 with t = 0 being the year 2000, while predictions based on Flint biosolids data is averaged over 4-month intervals (Dec–Mar, Apr–Jul, Aug–Nov) for Dec 2009–Jul 2015 and t = 0 represented by Apr-Jul 2014. Citizen science FWC sampling months were Aug 2015, Mar 2016, Jul 2016, Nov 2016, Jul 2017 at t = +1 to +3 years). For FWC, June 2014, is the only month where biosolids-predicted MWLL90 was in the range of the D.C. crisis.

of much longer duration (Edwards et al., 2009; Edwards, 2013; Roy and Edwards, 2019a). Specifically, the MWLL90 for the FWC, without considering the outlier month of June 2014, ranged from 10.2 μg/L to 43.1 μg/L, whereas that for Washington D.C. 2001–04 were between 61.9 μg/L and 108.6 μg/L. This is expected, since the D.C. lead crisis elevated a significant percentage of children's blood lead above the 10 μg/dL CDC "level of concern" in force at that time, whereas the FWC was manifested at the %EBL5 level and not at > 10 μg/dL (Edwards et al., 2009; Edwards, 2013; Hanna-Attisha et al., 2016; Gómez et al., 2018). Future studies examining possible public health harm from lead and other metals released from the plumbing during the FWC, should also carefully consider results indicating June–August 2014 was the time period of maximum water lead exposure.

3.6. Innovative use of biosolids monitoring data as a cumulative measure of WLLs

Urban sewage is being increasingly monitored to identify and map general public health trends from antibiotic resistance genes (ARGs), pharmaceutical and personal care products (PPCPs) and population-level traits like obesity and the human gut microbiome (Cai et al., 2014; Newton et al., 2015; Olofsson et al., 2012; Su et al., 2017; Wang and Wang, 2016). This study suggests that biosolids monitoring can provide important insights about overall trends in lead release to water from plumbing, which is important given rising worldwide concern about exposure to lead in drinking water, and the logistical and statistical problems of monitoring lead at consumer taps (Roy and Edwards, 2019a).

Targeted sampling, random sampling, 3-D profiles and proportional sampling of drinking water in consumer homes – all have acknowledged strengths and weaknesses, proponents and detractors (Clark et al., 2014; Del Toral et al., 2013; Masters et al., 2016a; Pieper et al., 2017; Schock, 1990; Jarvis et al., 2018; Lytle et al., 2019; Riblet et al., 2019), and, in some cases, a hundred household samples are required by regulation to calculate 90th percentile lead and monitor effectiveness of corrosion control for just one month each year. If a single sample of sludge could be used to track aggregate lead release and corrosion control effectiveness every month, as seems to have been the case in this research, it could improve understanding of seasonal trends and problems

with semi-random particulate lead release plaguing at the tap analysis of LCR monitoring data.

Specifically, biosolids lead monitoring may provide highly complementary, if not some superior, insights to traditional approaches that rely on direct monitoring of lead in drinking water at consumer taps. This is an exciting prospect deserving of future study that even seems obvious in retrospect given prior understanding. It is especially important considering the cost, logistical problems of accessing sampling taps in home and buildings for compliance sample collection, and the hundreds (or even thousands) of samples that would be required to obtain statistically valid estimates of water lead regulatory goals (i.e., 90^{th} percentile lead in the U.S.) as indicated by prior research (Masters et al., 2016a).

4. Conclusions

Our novel approach shedding light on WLLs during the FWC based on routine biosolids analysis revealed that:

- Plumbing-related metals, including lead, were strongly correlated with one another in monthly sewage biosolids monitoring data during 2011–17, especially during the FWC months of Apr 2014–Oct 2015.
- The plumbing related metals Cu, Zn and Pb were also correlated with one another in calculated weighted averages of first, second and third draw, in five rounds of Virginia Tech and USEPA drinking water monitoring data.
- Biosolids lead strongly correlated with citywide WLLs in Virginia Tech's sampling from August 2015 to August 2017.
- During the FWC, the increased biosolids lead mass ($\approx$23 kg) was just 14% higher than the comparable 18-month time period pre-FWC, but most (76%) of that increased mass was in the months of July–September 2014. During those three months %EBL5 was nearly doubled ($p < 0.05$) during FWC versus pre-FWC, but was not significantly higher in the other months of the FWC.
- Biosolids lead was very weakly correlated with %EBL5 pre-FWC and during the FWC, and not at other time periods, consistent with the expectation that water lead exposure is not strongly correlated to blood lead.
- Lead filters and bottled water severed the link between biosolids lead and %EBL5, consistent with public health protections of Flint consumers during the Federal Emergency.
- Exposure to elevated water lead during the FWC was predominantly associated with a large lead release that occurred during summer 2014, as evidenced by high lead in biosolids and %EBL5 in children. This is consistent with prior research based only on %EBL5.
- Summer spikes of WLL occurred when orthophosphate was not added to water in 2014 and 2015, but not in pre-FWC or post-FWC summer months when orthophosphate was being dosed.
- Higher orthophosphate dosages resulted in lower WLLs and biosolids lead levels, demonstrating the effectiveness of increased phosphate dosing.
- Biosolids lead monitoring may provide unique insights to effectiveness of lead corrosion control and citywide exposure risks.
- Biosolids lead and predicted human water lead exposures, during the 2014–2015 FWC, were in the range of what occurred in 2011.

Declaration of interests

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

> Aside from our work exposing the Flint water crisis, our data and testimony have been subpoenaed in several Flint water-related lawsuits. We are not party to any of the lawsuits. Dr. Edwards has been subpoenaed as a fact witness in many of the lawsuits, but he has refused all financial compensation for time spent on those activities. Previously, Dr. Edwards served as an uncompensated fact witness in lawsuits pertaining to Washington DC lead-in drinking water crisis, but these lawsuits have ended.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.watres.2019.05.091.

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Supplementary Information

Lead Release to Potable Water during the Flint, Michigan Water Crisis as revealed by Routine Biosolids Monitoring Data

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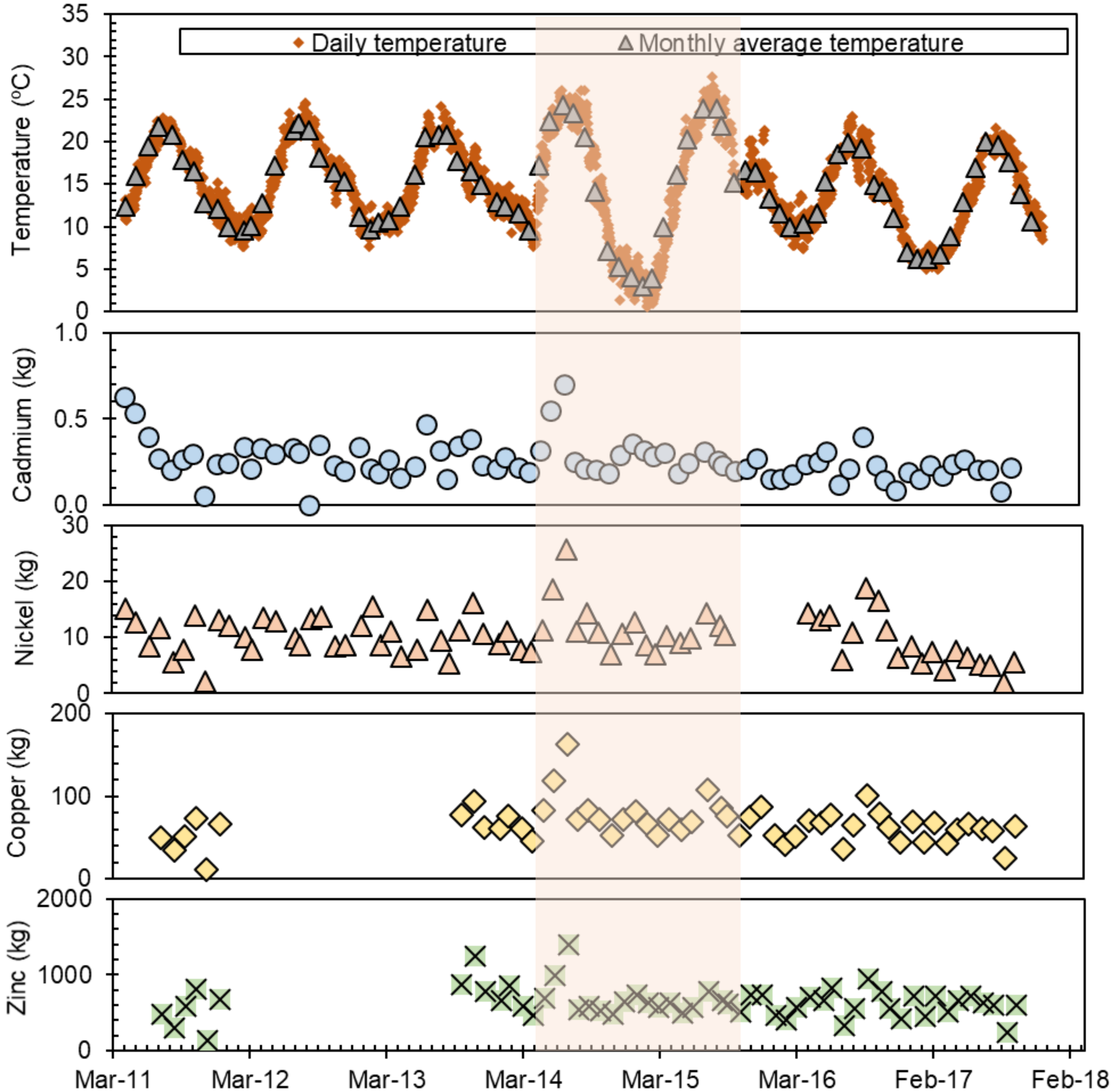

Figure S1. Monthly cumulative cadmium, nickel, copper and zinc mass in biosolids (kg) and water temperature during May 2011-November 2017. The orange area represents the FWC time span (April 2014-October 2015).

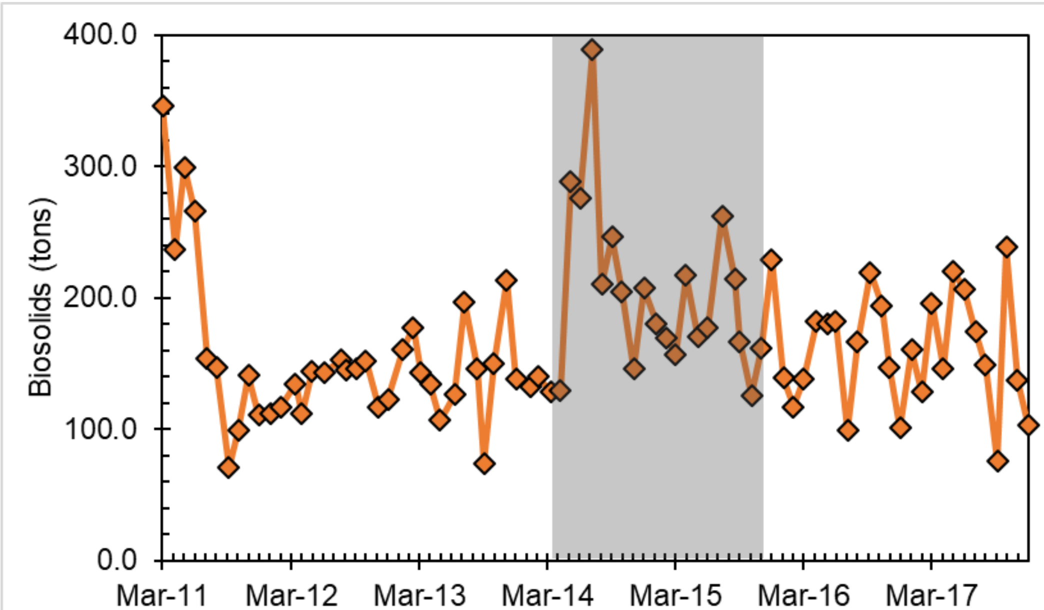

Figure S2. Total mass of biosolids (kilotons) produced at Flint's Wastewater Treatment Plant March 2011 - Dec 2017. The highlighted time period reflects biosolids for the Flint Water Crisis months April 2014-Oct 2015.

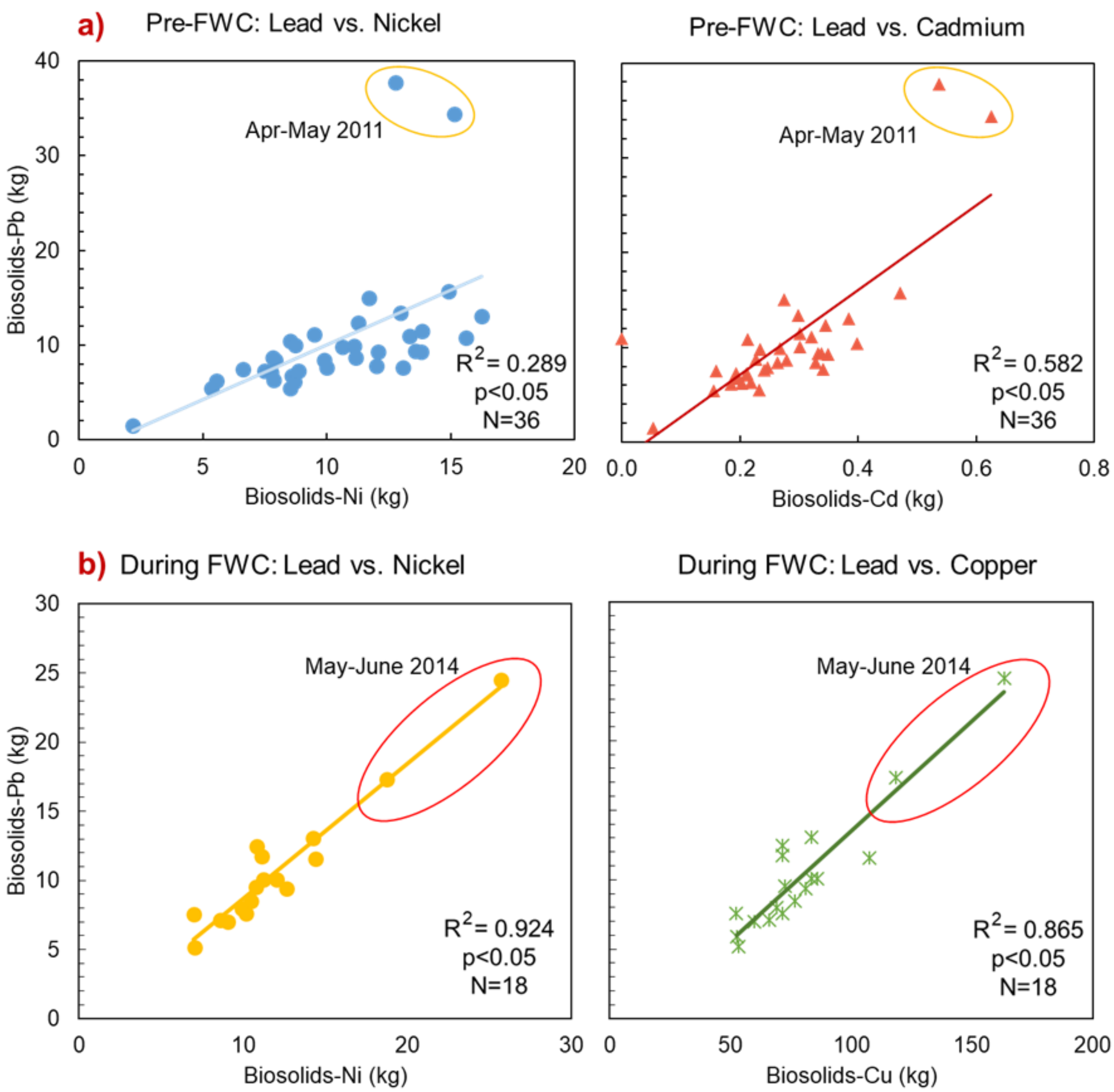

Figure S3. Cumulative lead mass in biosolids was (a) temporarily uncorrelated with other cumulative mass of metals originating from plumbing corrosion in 2011 (pre-FWC) implying a lead spike from an alternative environmental lead source, but was (b) highly correlated in 2014 (during FWC) with plumbing metals indicating increased plumbing corrosion from Flint River water.

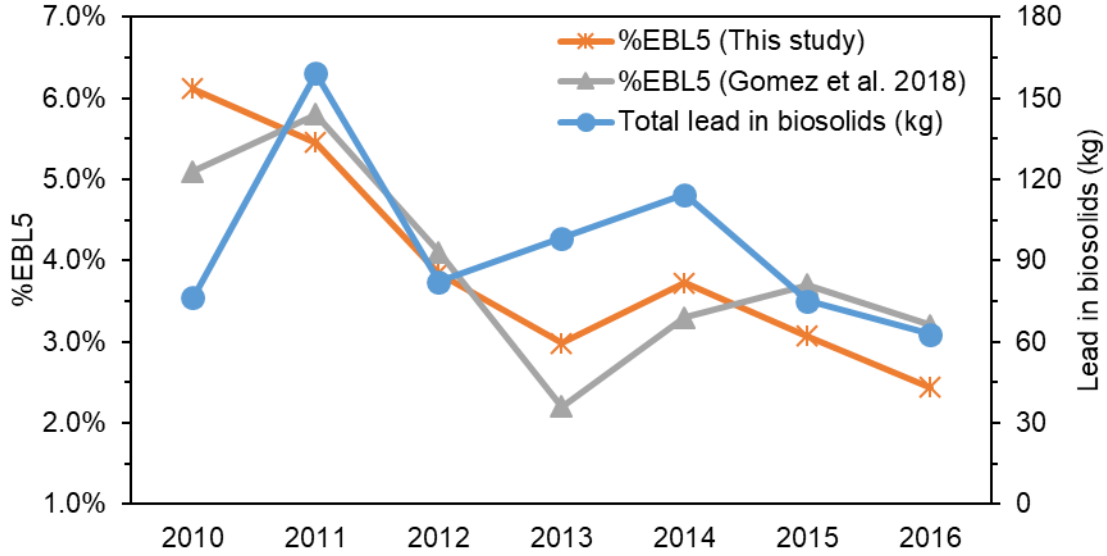

Figure S4. Trends of annual lead in biosolids (kg) from plumbing (i.e., obtained by subtracting 21.48 kg lead [or 1.79 kg lead/month x 12 months] from non-plumbing sources from total cumulative lead in biosolids) alongside corresponding annual %EBL5 from this study and Gomez et al. (2018).

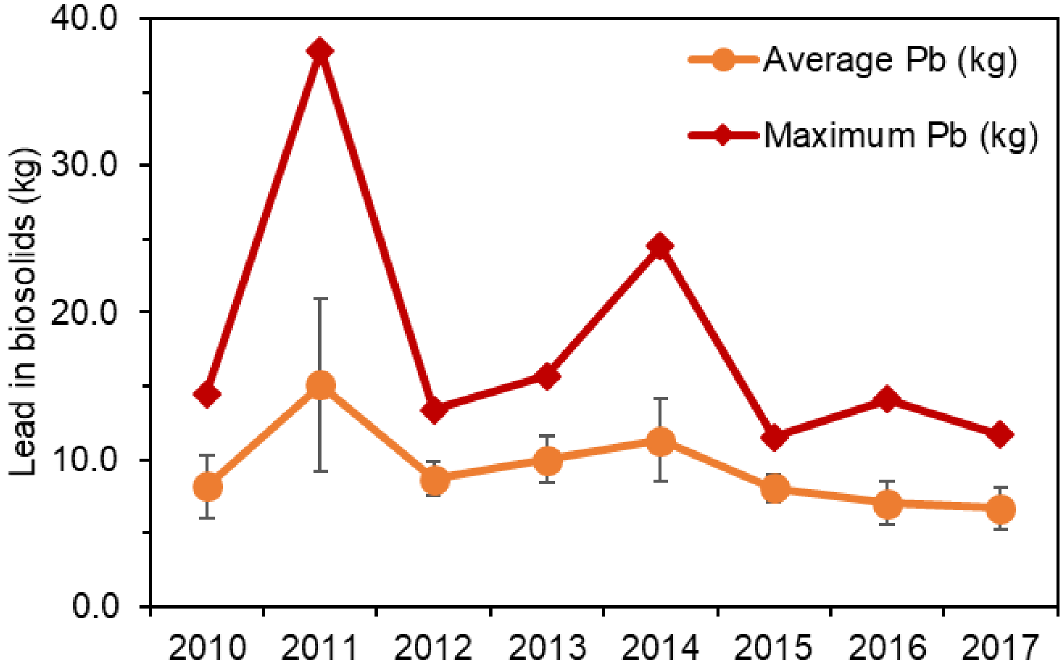

Figure S5. Average and maximum cumulative lead mass in biosolids (kg) per month in Flint. Error bars indicate 95% confidence interval.

Table S1. Hypothesized and actual correlations (Pearson's) between lead in biosolids, temperature and % EBL5 pre-, during and post- FWC.

Correlation between monthly lead in biosolids and	**Hypothesized**			**Actual**		
	Pre-FWC	**During FWC**	**Post-FWC**	**Pre-FWC**	**During FWC**	**Post-FWC**
monthly average temperature	No	Yes	No	No p=0.552 R^2=0.01	Yes p=0.018 R^2=0.301	No p=0.388 R^2=0.032
monthly % EBL5	No	Yes	No	Yes p=0.034 R^2=0.123	Yes p=0.049 R^2=0.221	No p=0.145 R^2=0.09

Table S2. Time periods pertaining to the Flint Water Crisis analyzed in this study.

Time period	**Label**	**Rationale**
May 2011-April 2014	pre-FWC	Flint buying treated Lake Huron water from Detroit since 1967; added corrosion control treatment (Pieper et al. 2017)
May 2014-October 2015	during FWC	Water switch to highly corrosive Flint River on April 25, 2014 and interruption of corrosion control; switchback to Detroit water on October 16, 2015 following public revelations of high water lead and high blood lead (Masten et al. 2016)
November 2015-November 2017	post-FWC	Provision of bottled water and filters, continued healing of pipes being served Detroit water, boosted corrosion control treatment (3X) starting December 9 2015 to hasten formation of stable lead scale (Pieper et al. 2018)

Table S3. Pearson's correlations between plumbing-related metals in biosolids pre-, during and post- FWC ($p<0.05$).

	Pre (05-11 to 04-14)		During (05-14 to 10-15)		Post (11-15 to 11-17)	
	R^2	p	R^2	p	R^2	p
Pb vs. Cd	0.588	5.02E-08	0.651	5.09E-05	0.799	1.67E-09
Pb vs. Cu	0.473	9.33E-03	0.865	2.39E-08	0.694	2.33E-07
Pb vs. Ni	0.286	7.64E-04	0.922	1.05E-09	0.421	1.98E-03
Pb vs. Zn	0.669	6.25E-04	0.762	2.20E-06	0.733	4.91E-08
Cd vs. Cu	0.805	3.29E-05	0.780	1.25E-06	0.797	2.00E-09
Cd vs. Ni	0.300	5.36E-04	0.746	7.68E-06	0.506	4.43E-04
Cd vs. Zn	0.762	9.86E-05	0.937	5.52E-11	0.837	1.63E-10
Cu vs. Ni	0.817	2.23E-05	0.962	4.50E-12	0.724	2.01E-06
Cu vs. Zn	0.937	6.10E-08	0.924	2.55E-10	0.908	1.93E-13
Ni vs. Zn	0.780	6.46E-05	0.880	2.72E-08	0.573	1.11E-04

Table S4. Pearson's correlations between plumbing-related metals in water during a) five Virginia Tech sampling rounds (Aug 2015, Mar 2016, Jul 2016, Nov 2016 and Aug 2017) and b) five USEPA sequential sampling events in 23 homes (Jan-Mar 2016, May 2016, Jul 2016, Sep 2016, and Nov 2016).

Virginia Tech	**Pb vs. Cu**		**Pb vs. Zn**		**Cu vs. Zn**	
	R^2	p	R^2	p	R^2	p
First Draw Mean (FDM)	0.638	0.100	0.270	0.369	0.856	0.024
Second Draw Mean (SDM)	0.899	0.014	0.629	0.110	0.464	0.205
Third Draw Mean (TDM)	0.000	0.975	0.023	0.409	0.209	0.439
1/3 (FDM) + 1/3 x (SDM) + 1/3 (TDM)	0.893	0.015	0.579	0.135	0.828	0.032

USEPA	**Pb vs. Cu**		**Pb vs. Zn**		**Cu vs. Zn**	
	R^2	p	R^2	p	R^2	p
First Draw Mean (FDM)	0.536	0.160	0.280	0.359	0.780	0.047
Second Draw Mean (SDM)	0.843	0.073	0.576	0.136	0.947	0.005
Third Draw Mean (TDM)	0.992	0.001	0.460	0.209	0.564	0.143
1/3 (FDM) + 1/3 x (SDM) + 1/3 (TDM)	0.925	0.009	0.540	0.157	0.783	0.046

EXHIBIT 3

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Efficacy of corrosion control and pipe replacement in reducing citywide lead exposure during the Flint, MI water system recovery†

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Flint biosolids monitoring data demonstrate a sustained decline in total lead release to potable water from plumbing since the 2014–2015 Flint Water Crisis (FWC), due to enhanced corrosion control treatment (3 mg L^{-1} orthophosphate as PO_4) and removing of ~80% of lead and galvanized iron service lines through early 2020. The official 90th percentile water lead levels, which have now met the federal Lead and Copper Rule threshold of 15 μg L^{-1} for the last four years, are in agreement with those predicted by a previously established biosolids regression model. There is also no longer a correlation between the percentage of children under 6 years of age with blood lead ≥ 5 μg dL^{-1} and biosolids lead mass in the 44 months post-FWC (Nov 2015–Jun 2019), nor are there continued correlations between plumbing-related metals in the biosolids, with the exception of Cu:Zn found in brass alloys that remain installed in homes. After Flint achieves 100% replacement of lead and galvanized service line pipes, a biosolids data analysis predicts that the remaining sources of waterborne lead including leaded brass, lead solder and legacy lead in pipe scale, will still release about 16–28% of the pre-FWC lead mass to potable water. The efficacy of enhanced corrosion control and replacement of service lines that contain lead is, therefore, on the order of 72–84% effective at reducing citywide lead exposure, yet some significant water lead sources will still remain even after pipe replacement is complete.

Water impact

In the aftermath of the Flint, Michigan Water Crisis (FWC) and a new proposed US Environmental Protection Agency (EPA) Lead and Copper Rule (LCR), the benefits of replacing lead service lines and implementing enhanced corrosion control to reduce water lead exposure are of high interest. Here we provide a novel analysis of routine Flint biosolids monitoring data, demonstrating a substantial 72–84% citywide reduction in the mass of lead released to potable water *vis-à-vis* pre-FWC 2013 year. Biosolids monitoring has certain advantages in tracking overall source reductions compared to traditional first draw sampling in a subset of homes with lead service lines.

Introduction

When the City of Flint, Michigan switched water sources from Lake Huron to the Flint River in April 2014 and stopped adding orthophosphate corrosion control,[1–3] higher levels of lead, iron, chlorine decay, deaths from Legionnaire's disease and blood lead in children resulted.[3–9] After the scope of the water lead problem became apparent, public outcry caused the city to switch back to Lake Huron water in October 2015 and the orthophosphate dose was tripled in December 2015.[2,5]

A federal emergency was declared in January 2016, and water lead levels (WLLs) have consistently measured below federal Lead and Copper Rule (LCR) standards since early 2017.[4–6,10] WLLs have even met the more rigorous provisionally adopted Michigan LCR standards since early 2019.[11,12] The officially reported WLL data is consistent with second, third and even fourth party independent analyses of lead in Flint water.[4,13,14] The city has also replaced thousands of leaded brass faucets, and 9516 service lines representing about ~80% of the city's total lead and galvanized iron pipes between March 2016 and March 2020.[15–18] Officials were even having trouble finding enough homes with verified lead service lines to successfully conduct the late 2019 LCR sampling event.[19]

Many Flint residents still do not trust the safety of tap water for a variety of reasons, including:

1) Actual cheating on official water lead testing before the crisis was exposed by the authors of this paper late 2015, and resulting betrayal of the public trust due to proven inaction, apathy and/or cover-ups by local, state and federal government agencies,[5,20–22]

2) In post federal emergency Flint (2016–19), some residents engaged in improper sampling, and in one case

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lead fishing sinkers were even discovered in a consumer's plumbing, producing water samples with very high WLLs (>12 000 μg L^{-1}) and suggestions of an ongoing health threat,[23]

3) Social media postings and investigative reports, by a "political reporter" from December 2016 to present, allege an ongoing conspiracy by government agencies and independent lead sampling programs to cover-up water lead problems,[23–26]

4) Widespread misinformation on the effectiveness of state-distributed lead filters,[27] and speculation by academics that the filters were causing Shigellosis or consumer deaths,[23,28–32]

5) Warnings that vibrations and other disturbances arising during pipe replacements, might also be causing massive release of lead from the Flint pipe network,[33,34] and unfounded assertions by some media, celebrities and politicians who continue to claim that Flint remains mired in a water lead crisis.[32,35–37]

We recently utilized data on the monthly lead mass captured in sewage sludge (or, biosolids) at the Flint wastewater treatment plant from 2010–17, to establish that biosolids lead reliably tracked lead release from plumbing to potable water before, during and in the immediate aftermath of the Flint Water Crisis.[38] This biosolids data has important advantages compared to official WLL monitoring data collected under the LCR, including: 1) biosolids samples represent a composite of all lead released to Flint's potable water over a several week time period, 2) the sampling methodology and location have remained the same for over a decade, and 3) this data has been collected by entities who are independent of those engaged in measuring water lead in homes.

In contrast, the official 90th percentile WLL only measures lead in the first liter from the tap (*i.e.*, "first draw"), has used first draw sampling protocols that have changed substantially in the last few years, is calculated from sampling pool of only 60–200 "high risk" homes with lead pipe that has been changing as lead service lines (LSLs) are replaced.[4] The official 90th percentile data is therefore designed to infrequently (once every three years to twice a year) identify a characteristic level of water lead in "worst case" homes, and does not reflect average or total lead release to water across the entire city. Thus, analysis and monitoring of the lead mass in Flint biosolids is complementary, and in some ways superior to traditional in home monitoring to track progress as the Flint system continues to heal from enhanced corrosion control and LSLs are replaced.

Herein, we apply our novel approach[38] to the most recent data on biosolids monitoring and elevated blood lead in children (January 2018–June 2019), which reflects a time period of unprecedented replacement of lead bearing (*i.e.*, lead and galvanized iron) service line pipe replacements. The tested hypotheses included the following: a) the State of Michigan, the US Environmental Protection Agency, and others, are providing a false sense of progress in terms of improving Flint WLLs and decreasing childhood lead exposure, b) the combination of pipe and faucet replacements, and corrosion control are reducing overall release of lead to water, and c) replacing lead pipes will greatly reduce (but not eliminate) lead release to drinking water due to remaining sources of lead from brass and solder in consumers' homes.

Materials and methods

Metals in biosolids

Monthly metal concentrations in biosolids (lead, cadmium, copper, nickel and zinc; mg kg^{-1} on a dried weight basis) measured per Standard Method SW 6020A[39] and total monthly biosolids production (kg) for January 2018–June 2019 were obtained from City of Flint's Water Pollution Control Plant *via* Freedom of Information Act (FOIA) requests. The monthly mass of metal in biosolids was calculated by multiplying the metal biosolids concentration by the total biosolids production. Metal mass in biosolids data for prior years (2010–17) for comparison were sourced from another study.[38]

Modeled relationship between biosolids lead and water lead levels

A regression model between lead in biosolids and in water for the City of Flint (eqn (1)) was used to estimate water lead levels (WLLs) from obtained biosolids lead data.[38]

$$\text{Biosolids-Pb (kg per month)} = 0.37 \times \text{WLL}_{90}\ (\mu\text{g L}^{-1}) + 1.41 \quad (1)$$

where, biosolids-Pb = biosolids lead mass in kg; WLL_{90} = composite 90th percentile water lead level in μg L^{-1}, estimated as a 50 : 50 weighted average of "first draw" and "second draw" WLLs.

The model assumes a one-month offset between biosolids-Pb and WLL_{90} (*i.e.*, biosolids-Pb measured in February 2018 is paired with WLL_{90} for January 2018) to account for a few weeks of biosolids and activated sludge detention times. The model also relies on the assumption that 90th percentile first draw lead ranges between 1.6 to 4.0 times the 90th percentile second draw lead in Flint, based on WLL data from five Virginia Tech citywide water sampling rounds between 2015–17.[38] This relationship was used to estimate a 90th percentile first draw range from the biosolids-predicted WLL_{90} values and compared against that calculated from official LCR testing for six month periods for 2016–19.[11] The only exception was 2019 where biosolids data corresponding to first five month period of WLLs (Jan–May 2019) was available.

Elevated blood lead levels

The de-identified aggregated monthly data on percentage of children under six with elevated blood lead 5 μg dL^{-1} (*i.e.*, % EBL5) during January 2018–June 2019, and from prior years

(2010–17) for comparison, were obtained from Hurley Medical Center's Dr. Mona Hanna-Attisha[40] and a previous study[38] respectively.

Statistical analyses

All statistical analyses were conducted in Microsoft® Excel® (version 2016) and IBM® SPSS (version 25). A p value of <0.05 with an alpha value (α) of 0.05 was selected to determine statistical significance. The coefficient of determination (R^2) was calculated to examine the associations between monthly biosolids metal masses for Pb, Cu and Zn.

Results and discussion

After examining trends on plumbing-related metals captured in biosolids from January 2018–June 2019, we use the established regression model between biosolids and water lead in Flint to estimate WLLs 2018–19 for comparison to reported (official and independent) 90th percentile WLLs. We then examine whether lead levels spiked or declined across the city, during implementation of Flint's unprecedented lead and galvanized service line pipe replacement program, and attempt to quantify the benefits and limitations of service line replacement in reducing WLLs.

Trends in plumbing metals captured in biosolids

Over 95% of treated wastewater in Flint is domestic in origin and most of the lead comes from corrosion of lead pipes and lead-bearing plumbing.[41–43] The lead mass in biosolids has continued to drop in the last few years (Fig. 1A) and reached another historic low in 2019. From January–June 2019, average lead was 5 kg per month (range = 1.2–8.5 kg per month), *versus* 10.2 kg per month (range = 5.2–24.5 kg per month) for the 18 months of FWC (April 2014–October 2015) and 9.3 kg per month (range = 5.4–15.7 kg per month) for a comparable period pre-FWC (April 2012–October 2013).

Biosolids masses for all five plumbing related metals (Cd, Cu, Ni, Pb, and Zn) during 2018–2019 also dropped to between 35–76% of that measured during the FWC, due to enhanced corrosion control, service line and lead faucet replacement (Fig. S1 in ESI†). While all three plumbing-related metals (Pb, Cu and Zn) in biosolids correlated before (2011–14), during (2014–15), and after the FWC (2015–17),[38] the only correlation that remained significant in this latest period of enhanced corrosion control and plumbing material replacement during 2018–19 was Cu *vs.* Zn (R^2 = 0.30; $p <$ 0.05). Copper and zinc are both present in the new brass alloy valves, faucets and fixtures that are still being installed throughout the Flint water system. Correlations between Pb:

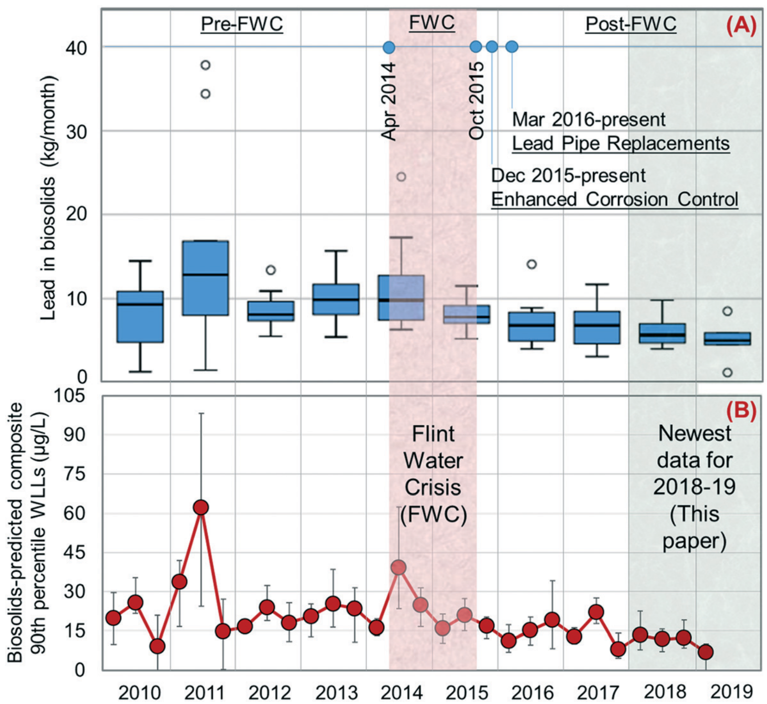

Fig. 1 (A) Box-and-whiskers plot of total monthly biosolids lead mass captured at the Flint wastewater plant, 2010–19. The open circles indicate outlier lead mass values. The plot summarizes data for January–December for 2010–18 and January–June for 2019. Enhanced corrosion control refers to tripling of orthophosphate corrosion inhibitor dose starting Dec 9, 2015. Lead pipe replacements began in March 2016 under the Flint FAST start program. Faucet replacements began in January 2017 with funding from State of Michigan. (B) Composite 90th percentile water lead levels (WLL_{90}) for Flint, MI predicted by a regression model (eqn (1)). The WLL_{90} values are derived from biosolids lead mass averaged over 4 month intervals (Dec–Mar, Apr–Jul, and Aug–Nov) for December 2009–March 2019. Error bars indicate the entire range of predicted WLL_{90} values (*i.e.*, minimum and maximum). Future models prospectively applying our approach, should also consider including a sensitivity analysis and error estimation, to further increase the statistical accuracy of the estimated WLL_{90} range.

Cu or Pb:Zn were no longer statistically significant ($p > 0.05$) (Table S1†).

All of the above is consistent with expectations based on the ongoing removal of lead pipes and the effectiveness of improved corrosion control.[18,38,44] Enhanced corrosion control has also essentially "decoupled" metal release from most of the different alloys that comprise the Flint water distribution system, including lead pipe, galvanized iron pipe, copper pipe, lead solder and brass (*i.e.*, copper, zinc, and lead).

Declining lead levels in Flint's potable water

Using the lead in biosolids data, the predicted composite WLL_{90} dropped below 10 ppb in 2019 for the first time in a decade, and was about 90% lower than that seen in the worst year pre-FWC (2011) and 83% lower than during the FWC (2014) (Fig. 1B). Morever, the official 90th percentile first draw WLLs for samples collected under the federal LCR, are in or within 1 ppb of the predicted WLL_{90} range, based on the calibration using data collected from July 2016–June 2019 (Fig. 2). For instance, the official 90th percentile first draw WLL for July–December 2018 of 4 $\mu g\ L^{-1}$ and the independent result of 4 $\mu g\ L^{-1}$ from third-party testing led by Michigan State University,[14] is at lower range of 4–8 $\mu g\ L^{-1}$ predicted by the model. This finding indicates that the conventional biosolids lead sampling is sometimes consistent with much more complicated first draw LCR sampling events in high risk homes with lead pipe.

The consistently decreasing water lead trends in Fig. 1 and 2, also demonstrate that concerns about WLL spikes following lead pipe replacements, did not overwhelm overall benefits from enhanced corrosion control and replacements of faucets, galvanized steel pipes and lead pipes.

Flint is about to enter a post-lead pipe era

The complete removal of LSLs will not eliminate lead release to drinking water. Lead solder, leaded brass, and premise plumbing that was "seeded" or coated with lead from LSLs in the preceding decades remain as significant lead sources. Roughly 95% of Flint homes were built in the pre-1986 time period when high lead content solder and brass was commonplace.[44,46,47]

To further highlight the importance of this issue, Flint resident X, who participated in five sampling rounds with the authors of this paper between August 2015–August 2017, had the highest WLL (1051 $\mu g\ L^{-1}$) in the August 2015 pool of 269 homes during the height of the water crisis.[4] We did a special investigation of this home, by paying to replace its entire home plumbing system except for the last few inches of pipe before the kitchen faucet, and we also examined the entire service line replaced by the city on the same day (March 9, 2016).[48] To our surprise, this worst case home did not have any pure lead or galvanized iron pipe—it had only lead solder and leaded brass. Sampling in four subsequent rounds determined Resident X's flushed sample WLLs to be consistently below 10 $\mu g\ L^{-1}$, whereas first draw WLL (Fig. 3) originating from the very short section of indoor plumbing continued to be as high as 230 ppb.[4]

Analysis of random tap samples that the authors of this paper analyzed from 138 Flint homes (Pieper *et al.*, 2018) in July 2016 before any lead or galvanized iron service line replacement, and again in August 2017 when ~30% (*i.e.*, 3624 homes) of service pipes were replaced, indicate that mean WLLs had dropped by just 6% at that time (Table S2†).[4] This raises the question, as to how effective the lead pipe and galvanized iron service line replacement program will be, in terms of reducing the mass of total lead released to water across the city.

Assuming that the total lead in biosolids is a summation of lead release from lead bearing service line pipes (lead and galvanized), indoor plumbing (*e.g.*, brass, solder, and lead coated onto indoor pipes from service lines), and non-plumbing sources, the biosolids lead can be described:

$$\text{Biosolids-Pb} = (\%\text{ services remaining}) \times Pb_{services} + Pb_{indoor} + Pb_{other} \quad (2)$$

Lead from other non-plumbing sources (*i.e.*, Pb_{other}) was estimated as 1.41–1.79 kg per month in our prior analysis.[38] We then solved for the remaining variables of lead from service pipes (or, $Pb_{services}$) and indoor plumbing (or, Pb_{indoor})

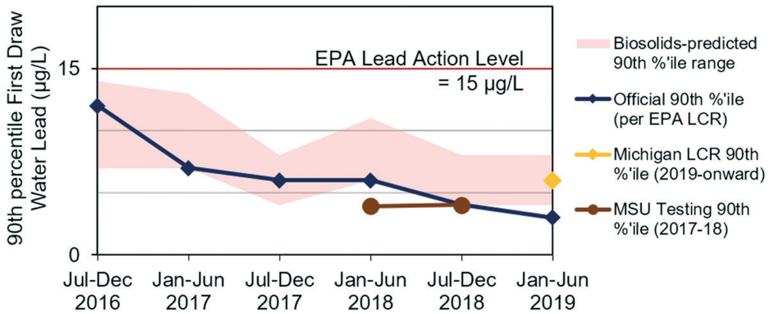

Fig. 2 Comparison in post-federal emergency Flint of 90th percentile first draw lead from official Lead and Copper Rule (LCR) sampling[11] against that predicted by the biosolids model (this paper), independent sampling led by Michigan State University or MSU,[14] and the new Michigan LCR that uses the highest WLLs of either first or fifth draw.[45] The 90th percentile first draw water lead "range" was calculated from the biosolids-predicted WLL_{90} using the first-draw-to-second-draw ratio of 1.6 (minimum) to 4.0 (maximum) observed in five water sampling rounds 2015–17.

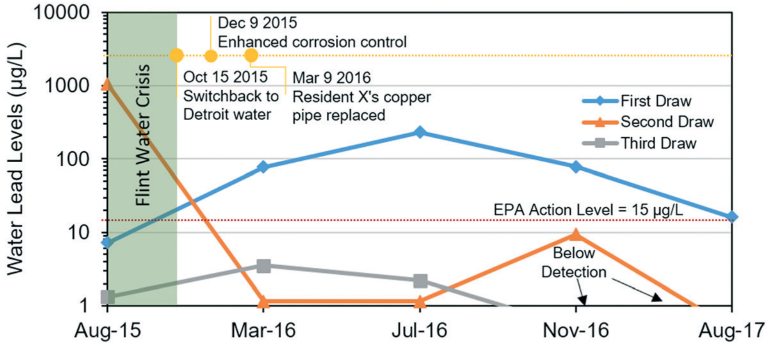

Fig. 3 Water lead levels (first draw, second draw, and third draw) in five sampling rounds during 2015–17 for resident X, who had a copper service line that was removed and replaced with a new copper pipe on March 9, 2016.

in eqn (2), during comparable periods of treated Lake Huron water as Flint's water source and stable phosphate corrosion control, for the years 2013, 2017 and 2018 when the percentage of service pipes in Flint's distribution system were 100%, 48%, and 34%, respectively (Fig. S3†) (see Text S1† for full solution). Projecting results to late 2020 when Flint will have replaced 100% of its lead and galvanized service pipes (*i.e.*, 0% of leaded service pipes remain), we calculate that that remaining sources of lead to water (*i.e.*, leaded brass, lead solder and also legacy lead in pipe scale) will still release about 16–28% of the 2013 pre-water crisis lead mass (Text S1:† Tables I [row G] and II [row G]) as expected.[13,46,49,50] The characteristic composite WLL due to remaining lead in plumbing would be 5.3–7.4 $\mu g\ L^{-1}$ (Text S1:† Table I [row H]). While this is a 67–77% improvement from pre-FWC 2013 year and an 82–87% reduction from the height of the FWC (Text S1:† Table I [row J]), it illustrates that the post-lead pipe era will not result in completely lead free drinking water.

Historically low incidence of elevated blood lead in children

In terms of childhood lead exposure in Flint, the mean % EBL5 levels for post-FWC months 1–18 (Nov 2015–Apr 2017) and months 19–44 (May 2017–Jun 2019), respectively dropped 55% and 63% below that seen in summer 2014 (Fig. S2†). There was no longer a relationship between biosolids lead and % EBL5, in the any post-FWC period ($p > 0.05$), as would be expected due to near elimination of exposure to waterborne lead from widespread use of bottled water and filters.[38,51,52]

A general survey of Flint residents (n = 1913) in December 2017 confirmed they were following recommendations of public health agencies to not drink unfiltered tap water, as 96% of respondents were using bottled water for cooking, 91.2% were even using it to brushing their teeth and 58.7% were even using it for bathing.[53] However, there has been a drop in overall household stress and fear regarding drinking, cooking, bathing, and brushing teeth with unfiltered tap water.[54] Overall, the analysis strongly supports continued reductions in release of lead to water in post-federal emergency Flint, Michigan.

Conclusions

This research supports the following conclusions about the City of Flint's recovery from high water lead levels that was first revealed through the collaborative work by the authors of this paper and Flint residents in August 2015:[4]

• Lead in biosolids reached a historical low in 2019, due to enhanced corrosion control and replacement of 80% of the lead and galvanized iron service pipes in Flint.

• Estimated composite water lead levels (*i.e.*, equally weighted first draw and second draw or service line WLLs) in 2019 have dropped 90% and 83% from worst levels seen before (2011) and during the Flint Water Crisis (2014), respectively.

• Official LCR 90th percentile first draw WLLs and independent WLLs, in 2016–19, were in good agreement with those predicted using a previously calibrated regression model relying on independent biosolids lead.

• The mean percentage of children ≤6yo with elevated blood lead (% EBL5) in the latest months (May 2017–Jun 2019) is at a historic low, and is 63% lower than that observed during the height of the FWC in summer 2014.

• There is no correlation between % EBL5 and biosolids lead mass in the 44 months post-FWC (Nov 2015–Jun 2019), supporting the reasonable expectation of low consumer water lead exposure during this time of bottled water and lead filters.

• The biosolids data support official data, that lead levels in Flint water are dropping, and do not support unfounded assertions that Flint water still has "crisis" levels of lead in water.

• As Flint approaches 100% lead pipe elimination, building plumbing (*i.e.*, brass and solder) sources of water lead will become dominant, and are estimated to represent 16–28% of the lead released to water in 2013 when all lead sources including service lines were present. The post-lead pipe era in Flint (or anywhere in America) will not result in lead free drinking water.

Conflicts of interest

Aside from our work with Flint residents exposing the water crisis in the first place, our data and testimony have been subpoenaed in several Flint water-related lawsuits. We are

not party to any of the lawsuits. Dr. Edwards has been subpoenaed as a fact witness in many of the lawsuits, but he has refused all financial compensation for time spent on those activities.

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Addendum: Efficacy of corrosion control and pipe replacement in reducing citywide lead exposure during the Flint, MI water system recovery

DOI: 10.1039/d1ew90023d

rsc.li/es-water

Addendum for 'Efficacy of corrosion control and pipe replacement in reducing citywide lead exposure during the Flint, MI water system recovery' by Siddhartha Roy and Marc Edwards, *Environ. Sci.: Water Res. Technol.*, 2020, **6**, 3024–3031, DOI: 10.1039/D0EW00583E

In the references section, references 21, 25 and 42 should be corrected as follows:

21. M. A. Edwards, Institutional scientific misconduct at U.S. Public health agencies: how malevolent government betrayed Flint, MI. Testimony to the U.S. Cong. Committee on oversight and government reform on examining federal administration of the safe drinking water act in Flint, Michigan hearing, *112th Congress 2nd session*, 2016, https://oversight.house.gov/sites/democrats.oversight.house.gov/files/documents/Edwards-VA%20Tech%20Statement%202-3%20Flint%20Water.pdf (accessed May 2021)

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The section beginning "Many Flint residents…" in the Introduction of this article should read as follows:

Many Flint residents still do not trust the safety of tap water for a variety of reasons, including:

1) Misreported official water lead testing before the crisis was exposed by the authors of this paper in late 2015, and resulting public mistrust of local, state and federal government agencies,[5,20–22]

2) In post federal emergency Flint (2016–19), some residents engaged in improper sampling, and in one case lead fishing sinkers were discovered in a consumer's plumbing, producing water samples with very high WLLs ($>12\,000\ \mu g\ L^{-1}$) and suggestions of an ongoing health threat,[23]

3) Social media posts and investigative reports, by a "political reporter"[24] from December 2016 to present, allege an ongoing conspiracy by government agencies and independent lead sampling programs to cover-up water lead problems,[23–26]

4) Widespread misinformation on the effectiveness of state-distributed lead filters,[27] and speculation by academics that the filters were causing Shigellosis[23] or consumer deaths,[28–32]

5) Warnings that vibrations and other disturbances arising during pipe replacements, might also be causing massive release of lead from the Flint pipe network,[33,34] and unfounded assertions by some media, celebrities and politicians who continue to claim that Flint remains mired in a water lead crisis.[32,35–37]

We recently utilized data on the monthly lead mass captured in sewage sludge (or biosolids) at the Flint wastewater treatment plant from 2010–17, to establish that biosolids lead reliably tracked lead release from plumbing to potable water before, during and in the immediate aftermath of the Flint Water Crisis.[38] This biosolids data has important advantages compared to official WLL monitoring data collected under the LCR, including: 1) biosolids samples represent a composite of all lead released to Flint's potable water over a time period of several weeks, 2) the sampling methodology and location have remained the same for over a decade, and 3) this data has been collected by entities who are independent of those engaged in measuring water lead in homes.

In contrast, the official 90th percentile WLL only measures lead in the first litre from the tap (*i.e.*, "first draw"). This sampling protocol has changed substantially in the last few years, and is calculated from a sampling pool of only 60–200 "high risk" homes with lead pipe that has been changing as lead service lines (LSLs) are replaced.[4] The official 90th percentile data is therefore designed to infrequently (once every three years to twice a year) identify a characteristic level of water lead in "worst case" homes, and does not reflect average or total lead release to water across the entire city. Thus, analysis and monitoring of the lead mass in Flint biosolids is complementary, and in some ways superior to traditional in home monitoring to track progress as the Flint system continues to heal through enhanced corrosion control, and LSLs are replaced.

Herein, we apply our novel approach[38] to the most recent data on biosolids monitoring and elevated blood lead in children (January 2018–June 2019), which reflects a time period of unprecedented replacement of lead bearing (*i.e.*, lead and galvanized iron) service line pipe replacements. The tested hypotheses included the following: a) the State of Michigan, the US Environmental Protection Agency, and others, are providing an inaccurate sense of progress in terms of improving Flint WLLs and decreasing childhood lead exposure, b) the combination of pipe and faucet replacements, and corrosion control are reducing overall release of lead to water, and c) replacing lead pipes will greatly reduce (but not eliminate) lead release to drinking water due to remaining sources of lead from brass and solder in consumers' homes.

Electronic Supplementary Information

Efficacy of Corrosion Control and Pipe Replacement in Reducing Citywide Lead Exposure during the Flint, MI Water System Recovery

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Text S1. Estimating percentage of biosolids lead that will continue to be released from indoor plumbing (16-28%) and composite 90th percentile water lead levels (or, WLL90) (5.3-7.4 μg/L) after Flint replaces all lead and galvanized service lines by late 2020.

Equation 1: *Biosolids-Pb = (% services remaining) x* $Pb_{services}$ + Pb_{indoor} + Pb_{other}

A. We use the following equation from Roy et al., 2019 that relies on composite water lead levels from first and second draws:[1]

Equation 2: *Biosolids-Pb (kg) = 0.37 x WLL90 (μg/L) + 1.41*, where

WLL90 = ½ x first draw + ½ second draw (Equation 2A)

Var.	Year	2013	2017	2018
A	**Total Biosolids-Pb (kg)**	117.7	77.6	72.9
B	**% services remaining**	100%	48%	34%
	• *Solving Equation 1 for both 2017 and 2018 against 2013 data*			
C	**$Pb_{services}$ (kg)**	--	77.1	67.9
D	**Pb_{indoor} + Pb_{other} (kg)**	--	40.6	49.8
E	**Pb_{other} (kg) for full year** = 1.41 x 12 = 16.9 kg (from Equation 2)			
F	**Pb_{indoor} (kg) = D – E**	--	23.7	32.9
G	**Percentage of Biosolids-Pb from plumbing = Pb_{indoor} / Total Biosolids-Pb or (F / A)**	--	20.1%	28.0%
	• *Assuming Flint replaces all service lines by end of 2020, % of pipes in system = 0%.* • *Therefore, Total Biosolids-Pb = Pb_{indoor} + Pb_{other} (Equation 3)* • *Dividing Equation 3 by 12 months to get Biosolids-Pb/month, substituting Equation 3 in Equation 1: $Pb_{plumbing+other}$ = 0.37 x WLL90 + 1.41, and solving for WLL90.*			
H	**WLL90 (μg/L)**	--	5.3	7.4
I	**Percentage WLL90 reduction against worst 3 FWC months (40.5 μg/L)**	--	86.9%	81.7%
J	**Percentage WLL90 reduction against pre-FWC year of 2013 (22.7 μg/L)**	--	76.7%	67.4%

II. We also use the following equation from Roy et al., 2019 that relies on composite water lead levels from first, second, and third draws:[1]

Equation 4: *Biosolids-Pb (kg/month) = 0.483 x WLL90 (μg/L) + 1.79*,

where *WLL90 = 1/3 x first draw + 1/3 second draw + 1/3 third draw*

(Equation 4A)

Var.	Year	2013	2017	2018
A	**Total Biosolids-Pb (kg)**	117.7	77.6	72.9
B	**% services remaining**	100%	48%	34%
	• *Solving Equation 2 for both 2017 and 2018 against 2013 data*			
C	**$Pb_{services}$ (kg)**	--	77.1	67.9
D	**Pb_{indoor} + Pb_{other} (kg)**	--	40.6	49.8
E	**Pb_{other} (kg) for full year** = 1.79 x 12 = 21.5 kg (from Equation 2)			
F	**Pb_{indoor} (kg) = D – E**	--	19.1	28.3
G	**Percentage of Biosolids-Pb from plumbing = Pb_{indoor} ∕ Total Biosolids-Pb or (F ∕ A)**	--	16.2%	24.1%

Text S1 References:

1. S. Roy, S., M. Tang and M. A. Edwards, Lead release to potable water during the Flint, Michigan water crisis as revealed by routine biosolids monitoring data, *Water Res.*, 2019, **160**, 475-483.

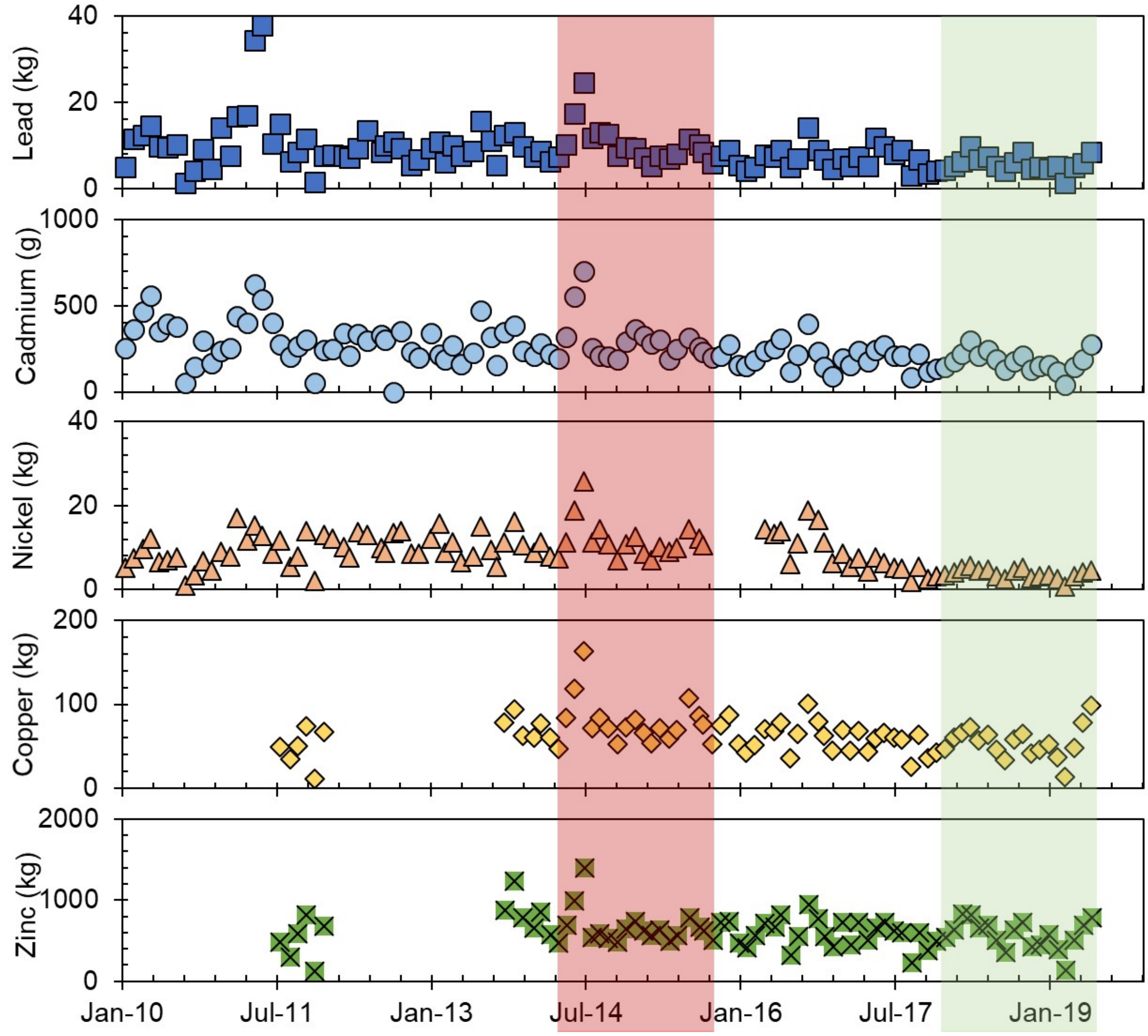


Figure S1. Monthly cumulative lead, cadmium, nickel, copper and zinc mass in biosolids (kg) during Jan 2010-Jun 2019. The red and green highlighted areas denotes biosolids metal levels during the 18 months of the Flint Water Crisis (April 2014-October 2015) and the most recent 18 month time period for which data is available (January 2018-June 2019).

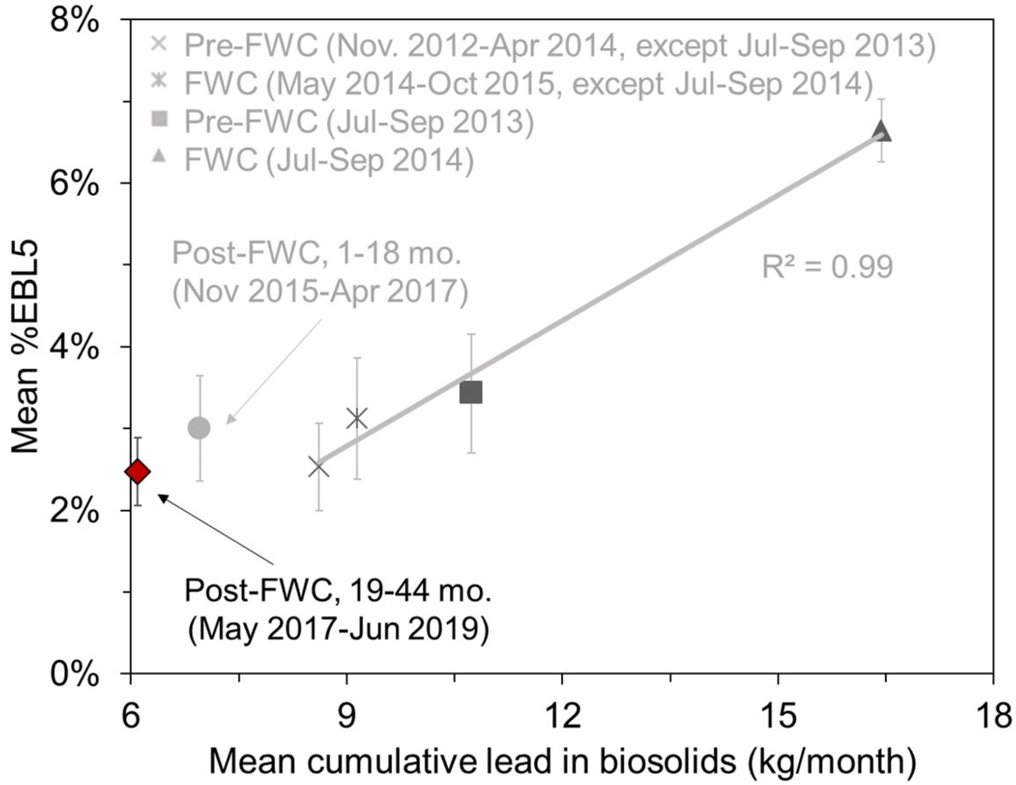


Figure S2. The latest post-FWC results of mean cumulative lead mass in biosolids (kg/month) and mean %EBL5 for May 2017-Jun 2019 (highlighted) are overlaid on the grayscale graph from Roy et al. 2019 described thus: Mean cumulative lead mass in biosolids (kg/month) correlated with mean %EBL5 for four time intervals pre- and during FWC ($R^2 = 0.99$, $p < 0.05$). Error bars indicate 95% confidence intervals for %EBL5. Due to water protective measures and a dramatic increase in EBL testing frequency by Federal Emergency Management Agency (FEMA), the post-FWC result is excluded from the regression.

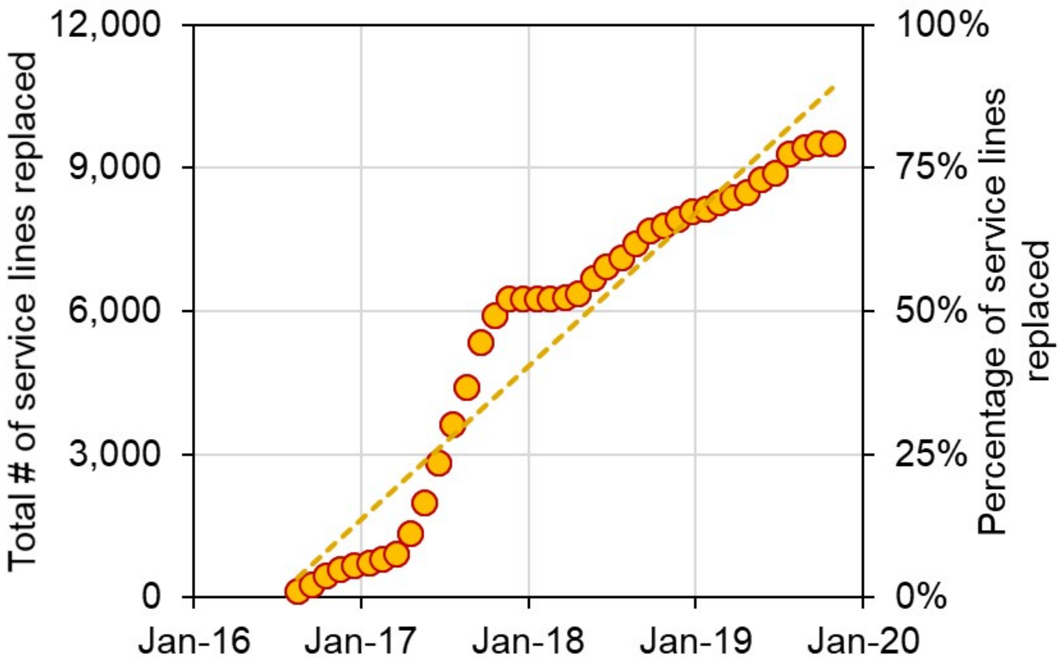


Figure S3. Total number and percentage of lead and galvanized iron service lines replaced in the City of Flint, 2016-19 (Data courtesy: Eric Schwartz [University of Michigan, Ann Arbor] and Jared Webb [BlueConduit]).

Table S1. Coefficient of determination (R^2) between plumbing-related metals mass measured in biosolids for January 2018-June 2019.

Metals	**R^2**	**p-value**
Pb vs. Cu	0.01957	0.5798
Pb vs. Zn	0.007	0.7348
Cu vs. Zn	0.3033	0.0178

Table S2. Reductions in mean WLLs between the July 2016 and August 2017 water sampling rounds in Flint homes (n=138) with enhanced corrosion control when approximately 30% (3,624) of lead and galvanized iron pipes had been replaced.

Sample \ Test Round	**July 2016**	**August 2017**	**% WLL reduction**
First Draw	9.6	9	5.8%
Second Draw	3.0	2.1	30.1%
Third Draw	2.4	1.8	23.7%
Composite WLL = *½ x first draw +* *½ x second draw*	6.3	5.6	12.0%

…

EXHIBIT 4

UNDARK

Opinion: From Sewage Sludge, a New Perspective on the Flint Water Crisis

The 2014 lead crisis was troubling. But the science now suggests that other cities — and even Flint — have seen worse.

By Siddhartha Roy and Marc Edwards 09.17.2020
Link: https://undark.org/2020/09/17/flint-water-crisis-sewage/

Sometime in 2021, a much-anticipated era of lead-free pipes will begin in Flint, Michigan. Contractors have replaced more than 90 percent of the city's pure lead and galvanized-iron pipes connecting homes to the water mains, and they are hard at work inspecting and replacing the roughly 2,500 that remain. Flint will likely become only the third major American city — after Lansing, Michigan and Madison, Wisconsin — to have replaced all its lead pipes. They are also the first to replace all the galvanized iron connections, another source of lead, and to pay for all the work without charging customers. Blood testing and residential water testing suggest that the lead levels in Flint water are now at historic lows.

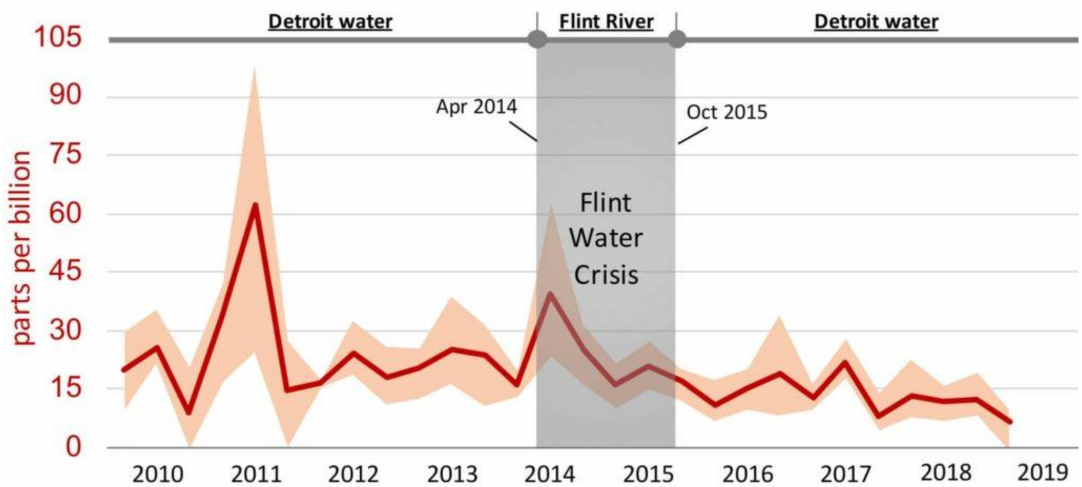
The improvements mark an end to Flint's disastrous history with lead pipes, which resurfaced in April 2014 when the city switched the source of its public water from Lake Huron treated by the city of Detroit to the Flint River, while discontinuing the use of corrosion control chemicals. The switch triggered an alarming rise in lead levels in the city's drinking water, a corresponding spike in children's blood lead levels, and a national scandal that led the city to switch back to water from Detroit in October 2015 while more than tripling the corrosion control dose. Ultimately, after revelations of deaths from two outbreaks of Legionnaire's disease caused by the initial switch, a federal emergency was declared by President Obama in January 2016.

Our early studies of lead levels in Flint residences helped expose the water crisis. Now, in complementary studies published in Water Research and Environmental Science: Water Research and Technology, we've found that lead levels in the water were not as bad as first feared: Water lead levels did increase sharply during the first few months of the water crisis, but for most of the time the city was receiving its water from the Flint River, the average levels of lead in drinking water were indistinguishable from those before the switch. In fact, our research shows that the Flint water crisis wasn't even the city's worst lead exposure event of that decade.

The conclusions are based on data collected from the routine monitoring of the city's sewage sludge, or biosolids. Well before taking samples at sewage plants became a popular way to track the surge of the novel coronavirus, scientists actively analyzed sewage to monitor aspects of public health, including viral disease markers, illicit drug consumption patterns, and human gut microbiome shifts. In Flint, officials have been sampling biosolids monthly for over 25 years.

We showed that lead levels in the biosolids were strongly correlated with lead levels from our citywide sampling of Flint's drinking water, which allowed us to use the biosolid measurements to estimate average lead levels in the city's drinking water over the period from 2010 to 2019. Due to consistency in the sampling methodology and the capture of all lead released from plumbing, the biosolids measurements in Flint's case provide a much more reliable picture of citywide water lead levels than the residential water tests, which were both infrequent and used questionable methods.

Water Lead Levels in Flint, Michigan



Water lead levels estimated from biosolids samples. The red line indicates mean 90th percentile water lead levels, averaged over four months. The highlighted range captures the minimum and maximum water lead levels over each averaging period.
Visual: Siddhartha Roy and Marc Edwards

We found that more than three quarters of the above-normal lead exposure during the water crisis occurred during June, July, and August of 2014. Contrary to speculation at the time, lead exposures during the rest of the 14-month crisis were in the same range as occurred before the switch. There was likely an initial spike of lead rust sloughing off pipe walls due to the discontinuation of corrosion inhibitors for the more corrosive Flint River water, which slowed down a few months into the crisis. This surprising trend is also confirmed in the blood lead data for Flint children.

Only during one month of Flint's water crisis, June 2014, did lead levels rise to a range comparable to those experienced during the country's worst water lead crisis of the 21st century. Between 2000 and 2004 in Washington D.C., the fraction of the infant population with lead levels above 10 µg/dL (that is, 10 micrograms per deciliter of blood), which was the Centers for Disease Control and Prevention's "level of concern" at the time, spiked to more than 5 percent. In Flint, the fraction of children with blood lead levels exceeding 10 µg/dL did not increase at all, although the fraction with blood lead levels exceeding 5 µg/dL, a new threshold instituted by the CDC in 2012, did rise significantly.

Interestingly, our work suggests that just four years before Flint's water made national headlines, the city suffered an even worse lead exposure event. We uncovered evidence of a previously undisclosed spike in water lead levels in mid-2011, when Flint was still receiving water from Detroit. That year, lead levels were estimated to have risen 50 percent higher than during the peak of the crisis following the switch to Flint River water. There is no obvious explanation for this increase, yet it mirrors a previously unexplained rise in children's blood lead, which was attributed to "random variation." This worrisome discovery reinforces the ever-present hazard of antiquated plumbing containing lead, even when corrosion control is in place and a water system is presumably operating normally, and, ultimately, to the importance of lead pipe replacements to eliminate the threat.

Our work suggests that just four years before Flint's water made national headlines, the city suffered an even worse lead exposure event.

The sewage data also confirms other studies that have shown dramatic improvements in Flint water's lead levels. Biosolids tracking suggests that the protective measures taken after Flint switched back to Detroit water — including tripling the dosage of corrosion control additives and free replacement of lead faucets and all lead and galvanized pipe connections to water mains — will ultimately reduce lead levels by between 72 percent and 84 percent of the pre-crisis levels.

Still, those measures will not translate to lead-free water, since our work demonstrates that brass faucets, lead solder, and galvanized iron that remain in Flint homes will continue to leach lead — as they do in homes all over the country. Even brand new "lead-free" plumbing cannot always guarantee water lead levels below the American Academy of Pediatrics' new recommendation of 1 part per billion for water in schools. Those facts should not detract attention from the major improvements in Flint's water, which has already been meeting all state and federal standards for contaminant levels over the past four years.

Regrettably, the legitimate fears of residents, compounded by misinformation, bad science, and conspiracy theories that have proliferated in the "scientific dark age" of post-water-crisis Flint, have continued to undermine public trust in the water and overshadow the successes of the government-led public health response.

As residents continue to wait for elusive justice for the environmental crimes in Flint and cautiously consider a historic $600 million settlement from the state of Michigan, we acknowledge that the lead exposures during the Flint water crisis were not as bad as first feared.

Siddhartha Roy is a postdoctoral researcher and Marc Edwards is a University Distinguished Professor, both at Virginia Tech. The authors' research team helped expose the lead and Legionella contamination problems in Flint's water during 2015.

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